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RESPONSE AND FEEDBACKS OF FOREST SYSTEMS TO GLOBAL CLIMATE CHANGE

Edited By: George A. King, Jack K. Winjum, Robert K. Dixon, and Lynn Y. Arnaut

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September, 1990

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Acknowledgments

Preface

This report was prepared by the Global Effects and Global Biogeochemistry Teams of the Global Change Research Program (GCRP) at the US Environmental Protection Agency's Environmental Research Laboratory in Corvallis, Oregon (ERL-C). The research was completed in cooperation with the USDA Forest Service, Oregon State University, the University of Virginia, the National Center for Atmospheric Research, and the International Institute for Applied Systems Analysis, as part of the ERL-C GCRP commitment to ORD for fiscal year 1990. The overall ORD GCRP plan identified two areas of research emphasis for ERL-C: 1) assess ecological impacts of climate change on terrestrial systems; and 2) determine the role of biospheric feedbacks to global climate change. This report addresses both ecological effects and biofeedbacks to global change as manifested through the global carbon cycle. Portions of this report have been presented at workshops and scientific meetings. Sections of this report have been (or will be) submitted to scientific journals or proceedings volumes for publication.

EXECUTIVE SUMMARY

A growing base of evidence suggests that the accumulation of greenhouse gases such as carbon dioxide (CO_2), methane, nitrous oxide, and chlorofluorocarbons in the atmosphere could significantly change the earth's climate. If this is true, forest systems throughout the world are projected to change in extent and composition. Biospheric feedbacks from forests to the atmosphere will also be altered in a changing global climate. Since a third of the biosphere's livable land is forested, such changes will dramatically affect humankind.

The purpose of this report is to summarize present knowledge in three areas: forest responses to climate change; the role of forest feedbacks to the atmosphere; and the potential of forest management to increase carbon sequestering. The report discusses these topics in the context of the global carbon cycle and the broader concept of managing the biosphere to offset increases in atmospheric CO_2. New research results are presented on the effects of vegetation redistribution on terrestrial carbon pools.

Alteration of global climate could result in a 20% to 60% change in vegetation cover type of terrestrial ecosystems. The responses of world forests to rapid climate change will vary by latitude. In the boreal region, where temperatures are projected to warm the most, forest boundaries are expected to migrate toward the poles. Within the temperate latitudes, warmer temperatures are expected to cause drier conditions for some regions, leading to forest declines. Migrations are likely to be slower than declines in both regions, thereby decreasing forest distributions. Closer to the equator, projections call for increases in precipitation, which would favor the productivity of moist tropical forests.

Numerous additional changes in forests are projected. For instance, forest species other than trees, both animal and plant, may experience stress while transitioning to changed climates. Some species are likely to disappear altogether, thereby reducing biological diversity. Other significant changes are related to increases in atmospheric CO_2. In addition to contributing to climate change, elevated CO_2 could produce a fertilizer effect in forests. That is, photosynthesis is favored by increased CO_2, and forest growth and productivity might increase where moisture is not limiting. At the same time, high levels of CO_2 are known to improve water-use efficiency in plants, and forests in drier areas could benefit from this effect.

Changes in global vegetation could cause terrestrial carbon storage to increase (using climate scenarios generated by the GISS and OSU Global Circulation Models, or GCMs) or decrease (UKMO and GFDL GCMs). Carbon cycling in changing forest ecosystems may shift and thereby alter the size of above-

and belowground carbon pools. Where forest regions are decreasing in size and vegetation is in transition to different environments, carbon could be emitted to the atmosphere, creating an undesirable positive feedback. Transient response of vegetation could increase atmospheric carbon by 0-3 gigatons (10^6 metric tons) annually. This is an area of great uncertainty, and much more needs to be learned for a clear understanding of the potential feedbacks.

A possible mitigation technique for slowing the increase of CO_2 in the atmosphere is increasing the amount of carbon stored in the terrestrial biosphere. Forests and other terrestrial components of the biosphere, such as agroecosystems, can be managed to sequester carbon and contribute to mitigation efforts. Of the many possible approaches, reforestation to create new productive forests and expansion of agroforestry systems offer the greatest potential to fix atmospheric CO_2. However, sociopolitical factors, investment capital, and effective technology currently limit all approaches to managing the carbon cycle.

RESPONSE AND FEEDBACKS OF FOREST SYSTEMS TO GLOBAL CLIMATE CHANGE

1 INTRODUCTION

A third of the world's lands are forested and people in all nations benefit by the contributions of forests to basic necessities (fuel, food, fiber) and to a functional terrestrial biosphere. Forests are not static, however. Through geologic time, for instance, natural changes in climate have greatly altered the extent and composition of forests throughout the world. The reverse is also true: forests can influence climate. For example, transpired water vapor and natural gas emissions from forests act as feedbacks that affect climate.

In recent millennia, anthropogenic activities have rivaled climate as an influence on forests. That is, throughout the world, humankind has used, abused, and, in some cases, sustainably managed forests in all major terrestrial regions. At the same time, human activities have grown in the last century to the point that they are now suspected of altering the atmosphere through emissions of waste chemicals and particulate matter. These changes in the atmosphere are projected to cause dramatic global warming in the next century (Intergovernmental Panel on Climate Change [IPCC] 1990).

Thus, in the climate-forest-human triad of today, each component can influence the condition of the other two. How this situation will play out in the coming decades is uncertain. What is the potential risk to the terrestrial biosphere, particularly to humankind, and can measures such as forest management offset the suspected adversities of rapid global change?

Investigating these questions has become a principal research initiative at the US Environmental Protection Agency's (EPA) Environmental Research Laboratory-Corvallis (ERL-C). In the last two years, ERL-C and other research groups have begun to address the response and feedbacks of the terrestrial biosphere to global change. New research approaches have produced insights and projections regarding global change and forest systems. This report is a current summary of scientific hypotheses and evidence regarding projected global change, as well as of new research on potential effects of climate change on terrestrial carbon pools.

1.1   Subject

Climate simulations using General Circulation Models (GCMs) suggest that the production of greenhouse gases (e.g., carbon dioxide, methane, chlorofluorocarbons, and nitrogen oxides) from anthropogenic activities could cause large changes in global climate. This results when atmospheric increases in these gases in trapping heat that is radiated outward from the earth's surface. By the year 2020, global mean temperature is predicted to rise 1.8°C above preindustrial levels, with a probable increase between 1.3 and 2.5°C (IPCC 1990). This change is often referred to as "global warming" or the "enhanced greenhouse effect." The accumulation of anthropogenic emissions and the potential impacts of the greenhouse effect on the biosphere have been reviewed extensively (Schneider 1989a, Smith and Tirpak 1989, IPCC 1990). Terrestrial ecosystems will be affected by greenhouse gases and a changing climate, and feedbacks from terrestrial systems to global climate change processes will be significant (Houghton 1987, Mooney et al. *in press*). This document focuses on forests, the most dominant component of world terrestrial ecosystems.

The global carbon cycle is a central process in climate change (Woodwell et al. 1983, Detwiler and Hall 1988, Prentice and Fung *in press*). This cycle includes all the biological and chemical processes that affect the circulation of carbon through the atmosphere, terrestrial biosphere, and oceans. World forests play a critical role in the conversion and storage of carbon in the terrestrial biosphere. Globally, forests contain approximately 90% of all aboveground terrestrial carbon and 40% of all belowground carbon (Waring and Schlesinger 1985). World forests may also account for up to two-thirds of global photosynthesis, with terrestrial plants removing approximately 110 gigatons (Gt) of carbon from the atmosphere annually through photosynthesis (Figure 1.1-1). At equilibrium, an equal amount of carbon is returned to the atmosphere through plant respiration and decay of organic matter. Fossil fuel combustion and global deforestation result in respective releases of approximately 6 Gt (Tans et al. 1990) and 1-2 Gt (Schneider 1989b) of carbon to the atmosphere each year (estimates of carbon release from deforestation are highly uncertain). The future carbon source-sink relationships of boreal, temperate, and tropical forests are therefore an important research priority.

Carbon dioxide (CO_2) concentrations in the preindustrial atmosphere have been estimated at 280 ppm, increasing to approximately 355 ppm in 1989 (Keeling 1989). Although vegetation processes significantly influence CO_2 concentrations in the atmosphere, the potential response of vegetation in terrestrial ecosystems to CO_2 enrichment and associated climate change is relatively unknown. For example, while the increase in atmospheric CO_2 contributes to global climate change, it also may stimulate growth of terrestrial vegetation. Short-term effects of CO_2 enrichment include improvements in

growth and water-use efficiency in plants growing in a CO_2-enriched environment (Eamus and Jarvis 1989, Strain and Cure 1985). Warm temperature, in the absence of moisture stress, has been shown to increase growth and maintenance respiration of some plants (Berry and Bjorkman 1980, Drake et al. *submitted*). Long-term responses of vegetation, especially forests, to the combined effect of global warming and CO_2 enrichment are uncertain (Mooney et al. *in press*).
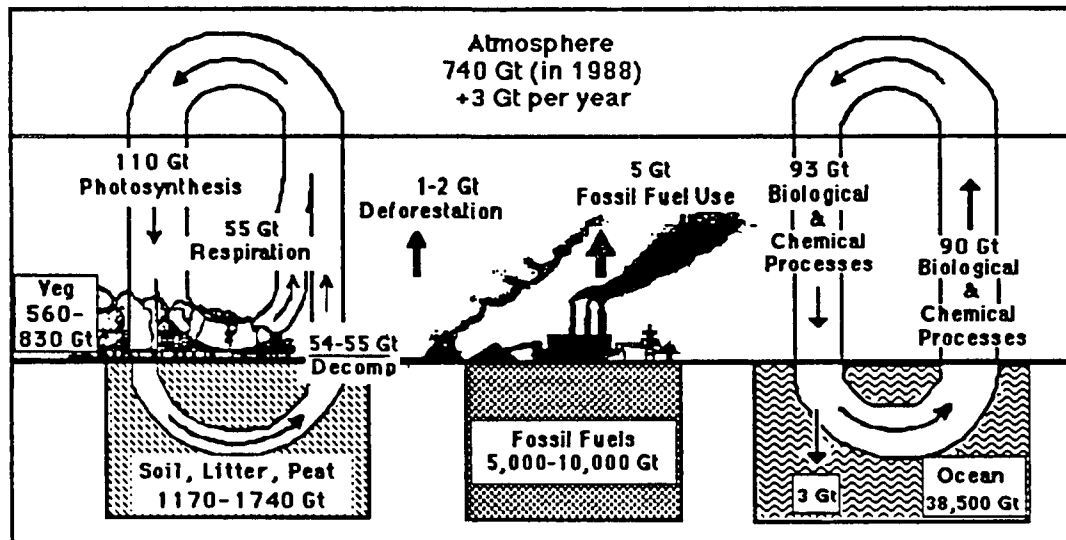
Figure 1.1-1. The global carbon cycle, including major pools and annual flux of carbon (adapted from Schneider 1989b).

Global climate change is predicted to significantly influence the condition, distribution, and migration of forests (Smith and Tirpak 1989, Neilson et al. 1989). Estimates of impacts on future forest condition, distribution, and productivity are based upon two types of models, GCMs and global vegetation models (Box 1981, Emanuel 1985, Emanuel et al. 1985, Prentice and Fung *in press*). GCMs are three-dimensional representations of the earth's atmosphere, and, although extremely complex, they produce only very rough estimates of climate change for the next few centuries. About six models are used widely, and their climate predictions vary substantially. Global vegetation models also vary widely in their predictions.

In summary, our knowledge of global change impacts and feedbacks on forest ecosystem-level carbon cycling is meager but growing rapidly. This report presents new results based on recent work at ERL-C on the potential changes in terrestrial carbon storage caused by vegetation redistribution (see Section 3) and a summary of the relevant scientific literature. A number of new research activities were initiated in FY90 (Appendix A). Emphasis is placed on results obtained since the 1989 EPA Report to Congress on the effects of climate change on resources of the United States (Smith and Tirpak 1989), and on topics not discussed in that report.

1.2. Scope

This report discusses the potential ecological responses and feedbacks of forest systems to a changing global climate. Forests will be considered on a global scale, including the boreal, temperate, and tropical forest regions. Specific topics to be discussed are:

1) The current knowledge of the effects of global climate change on forests (Section 2).

2) Potential changes in terrestrial carbon storage as vegetation responds to global climate change (Section 3).

3) Estimates of the effect of increases in atmospheric CO_2 on forest ecophysiological processes that influence carbon assimilation and cycling, especially water-use efficiency, photosynthesis, and respiration (Section 4).

4) The role of forest management, especially large-scale reforestation, in sequestering atmospheric CO_2 (Section 5).

5)   Management of the biosphere as an aid in mitigating global climate change (Section 5.3).

6)   Key research needs leading from uncertainties about the role of the terrestrial biosphere
      (Section 6).

1.3   EPA's 1989 Report to Congress

In the late 1980s, Congress requested that the EPA undertake two studies on "climate change due to the greenhouse effect." One study was to be on the potential effects of climate change on United States agriculture, forests, human health, water systems, and other vital resources (Smith and Tirpak 1989). The second study was to focus on "policy options to stabilize current levels of atmospheric greenhouse gas concentrations" (Lashof and Tirpak 1989).

In EPA's 1989 Report to Congress on global climate change, the Forest Effects chapter presented results of studies and projections after two years of analyses conducted by the Global Climate Team at ERL-C (Winjum and Neilson 1989). Principal findings and limitations reported at that time are reviewed in this section. This document builds on the earlier information and, in addition, it includes the following considerations about forests: 1) feedbacks to the atmosphere; 2) CO_2 mitigation potential; and 3) role in global ecology.

1.3.1 Findings

1)   Global warming could significantly impact forests of the United States, with the effects apparent
      in 30 to 80 years.

2)   The potential northern range of forest species in the eastern United States could shift northward
      by as much as 600 to 700 km over the next century. Actual northward migration could be
      limited to as little as 100 km because of slow natural rates of species migrations.

3)   The southern ranges of many eastern United States tree species could die back by as much as
      1000 km because of higher temperatures and drier soils. Together with the projections of the
      previous finding, distributions for some tree species would significantly decrease. Overall, forest
      productivity in the United States is likely to decline, especially along the southern edges of
      present forest regions.

4)   Additional impacts of climate change on forests could include increases in wildfire, insect and disease outbreaks, wind and air pollution damage, and soil erosion. A reduction in biodiversity is also projected (Barker et al. 1990).

5)   Regarding forest policy, institutions such as the United States Department of Agriculture's (USDA) Forest Service (USFS), state forest agencies, and private forest companies should consider climate change impacts in their long-term planning. A coordinated public and private reforestation effort, together with development of new and adapted silvicultural practices, may also be required.

1.3.2 Uncertainties

1)   Under conditions of rapid climate change, the response of entire forest ecosystems is very difficult to project. The 1989 studies were based upon available knowledge of major tree species, largely for eastern United States forests. Ecosystems, however, are composed of a myriad of both plant and animal species, each likely to have its own characteristic response. Ecosystem response, therefore, remains highly uncertain.

2)   The mathematical simulation models generated in the 1980s to simulate forest response to climate change did not include dispersal rates for the tree species studied, and therefore projections of forest migrations were only crudely estimated. Furthermore, the potential of aiding migration through reforestation practices was not analyzed in detail.

3)   Forest declines are often triggered by periods of high environmental stress. The forest models used for the studies in the 1989 Report to Congress were not run far beyond current conditions, such as for extremely dry soils. Therefore, the model projections may not estimate the timing and behavior of forest declines under future climate conditions as closely as desired.

4)   The response of mature trees or forests to elevated atmospheric CO_2 was not evaluated in the study for EPA's 1989 Report to Congress. At that time, few CO_2 response data were available for forest tree species, and the available information was for seedlings exposed to elevated CO_2 for a few growing seasons. This factor led to a large uncertainty in the early study results regarding response by forest stands whether under the present climate or with rapidly changing climate (and the uncertainty remains, as noted in Section 1.1).

5)   The 1989 Report to Congress focused exclusively on the United States. Effects of global climate change on world forests are uncertain.

1.4   Background

Three important background topics for the report are: 1) a brief description of the extent of world forests; 2) the role of forests in the global carbon cycle; and 3) the climate change scenarios that will affect both forests and the global carbon cycle. Though presented as background information, knowledge about each topic is incomplete primarily because their study on a global scale is relatively new.

1.4.1 World Forests

Forests were estimated in 1985 to cover 4139 million ha in the world, or about 31% of the total land area (Sedjo and Lyon 1990) (see Table 1.4-1). Another 1030 million ha, or 8%, is classified as shrubland and forest fallow (i.e., cleared, not fully reforested, but with scattered trees; Postel and Heise 1988) (see Table 1.4-2). The total by this classification, therefore, is about 38% of the world's land area as of 1985. Matthews (1983) estimated that in pre-agricultural history, world forests were about 15% greater in extent than they are today.

Table 1.4-1   World Forested Area by Region, circa 1985 (from Sedjo and Lyon 1990)

Region	Forestland[1]	Closed forest	Open woodland	Total land area	Closed forest	Total forest
		(million ha)			(percentage of land area)	
North America	734	459	275	1,829	25	40
Central America	65	60	2	272	22	24
South America	730	530	150	1,760	30	41
Africa	800	190	570	2,970	6	27
Europe	160	148	12	472	31	34
Soviet Union	930	792	138	2,240	35	42
Asia	530	400	60	2,700	15	20
Pacific Area (Oceania)	190	80	105	842	10	23
World	4,139	2,659	1,200	13,105	20	31

[1]Forestland is not always the sum of closed forest plus open woodland, as it includes scrub and brushland areas that are neither forest nor open woodland as well as deforested areas where forest regeneration is not taking place. In computation of total land area, Antarctica, Greenland, and Svalbard are not included; 19% of all Arctic regions are included.

Source: Economic Commission for Europe/Food and Agriculture Organization of the United Nations (ECE/FAO), The Forest Resources of the ECE Region (Geneva, ECE/FAO 1985).

Table 1.4-2   Forest Fallow and Shrubland, circa 1980 (Postel and Heise 1988)

Region	Area (million ha)
Asia (except China)	107
Africa	608
Central and South America	313
Oceania	2
Total	1,030

Forests are a significant component of the landscape on every continent and large island group in the world except Antarctica (Young 1982). They have historically contributed to human economic and social progress by providing such resources as shelter, fuel, food, water, recreation, and many commercial products (Perlin 1989). Some projections for global climate change suggest that the ability of forests to sequester (i.e., to capture and hold) vast quantities of carbon is yet another role of vital importance to humankind. In contrast, predictions from some global vegetation models suggest that forests could become major sources of carbon that might stimulate global climate change (Leemans 1990, Smith et al. *submitted*). Many forest classification systems appear in the literature (Young 1982). Often forests are classified as commercial and noncommercial. For example, the USFS calls forests commercial if they can grow 1.4 m³/ha/yr of wood that is of sufficient quality to justify timber harvests. Both commercial and noncommercial forests can be either coniferous, broadleaved, or a mixture (Young 1982). Noncommercial forests, though less productive in commercial wood yields than commercial forests, nevertheless have significant roles in providing resources such as food, water recreation and fuel wood, and sustaining biological diversity (Reid and Miller 1989).

Typically, ecological classifications are by tree density or crown cover. Closed forests are those in which the tree canopy cover is about 20% or more of the land surface (Westoby 1989). These forests grow where the annual precipitation is at least 400 mm. In drier areas, forests have more scattered trees so the canopy cover is less; where canopy cover is only about 5-20%, the plant communities are called woodlands (Young 1982).

Closed forests of the world represent about two-thirds of the forest land area and woodlands make up the other third (28.3 and 13.2 million ha, respectively; see Table 1.4-1). Closed forests are commonly classified as follows (Young 1982):

1) Mainly evergreen forests:
   a. broadleaved evergreen forests (primarily in warmer climates; e.g., moist tropical forests);
   b. coniferous forests (primarily in cooler climates; e.g., boreal and temperate forests);

2) Mainly deciduous forests:
   a. drought deciduous forests (leaves shed in dry season; e.g., dry tropical forests);
   b. cold deciduous forests (leaves shed in winter; e.g., temperate hardwood forests).

1.4.2 Global Carbon Cycle

The global carbon cycle links significant biogeochemical processes that affect the flux (movement) of carbon between the atmosphere, terrestrial biosphere, and ocean pools. Although the general outline of the cycle is well known, large uncertainties still exist in estimates of the magnitude of carbon pools and fluxes.

In general, the oceans store by far the largest fraction of carbon on the globe (38,500 Gt), followed by fossil fuels in the earth's crust (i.e., coal and oil; 5,000-10,000 Gt)(see Figure 1.1-1, Bolin et al. 1979, Schneider 1989a). For terrestrial ecosystems, estimates of aboveground carbon storage are highly uncertain, but they range from 560 to 830 Gt (Whittaker and Likens 1975, Schlesinger 1984, Post et al. 1979, Ajtay et al. 1979, Olson et al. 1983, Mooney et al. 1987, Schneider 1989a). The earth's atmosphere is estimated to have 740 Gt of carbon, about the same amount as terrestrial vegetation. Terrestrial soils, however, contain between 1.5 to 3 times as much carbon (1170 to 1740 Gt) as either terrestrial vegetation or the atmosphere.

Even though the terrestrial biosphere stores much less carbon than the amount stored in oceans, annual fluxes between the atmosphere and terrestrial biosphere are approximately equal to those between the atmosphere and oceans (excluding anthropogenic influences) (Figure 1.1-1). On an areal basis, therefore, terrestrial fluxes are much greater than oceanic fluxes. The total annual contribution to the atmosphere of carbon from the terrestrial biosphere and oceans is about 30% of that stored in the atmosphere, with an annual contribution back to these systems of about the same order of magnitude (Bolin et al. 1979, Schneider 1989b).

These characteristics of terrestrial biosphere fluxes imply that changes in land use and land management practices that might impact carbon fluxes (e.g., deforestation, reforestation, conservation of soil carbon) could have significant impacts on atmospheric CO_2 concentrations (as discussed in Section 5). That the terrestrial biosphere can affect atmospheric concentrations of CO_2 is best illustrated by the seasonal changes in atmospheric CO_2 (Figure 1.1-2) (Keeling et al. 1989, Tucker et al. 1986), which are caused by seasonal changes in the relative magnitude of photosynthesis and respiration in the biosphere (Mooney et al. 1987, King et al. 1987).

Of concern from the perspective of possible global climate change is that the fluxes into and out of the atmosphere are not balanced, and the atmosphere is gaining about 3 Gt of carbon per year (Schneider 1989b, Tans et al. 1990). The two principal sources of the additional atmospheric CO_2 are fossil fuel

combustion (Marland et al. 1989, Schneider 1989b) and deforestation (Woodwell et al. 1983, Palm et al. 1986, Houghton et al. 1983, Houghton et al. 1985, Houghton et al. 1987, Detwiler and Hall 1988). The contributions of these two carbon sources are about equal according to Keeling (1989), and the combined total (6-7 Gt) is almost <u>double</u> the 3 Gt of carbon accumulating in the atmosphere each year. Moreover, the contributions from the terrestrial biosphere (Keeling et al. 1989) and fossil fuel combustion are increasing with time.

One of the critical unknowns in balancing the carbon budget is determining where the carbon released to the atmosphere from deforestation and fossil fuel combustion is stored, since only about half accumulates in the atmosphere. The only two possibilities are the oceans and the terrestrial biosphere. A recent study suggests that the terrestrial biosphere (primarily at temperate latitudes) is a greater sink for the remaining carbon than previously thought (Tans et al. 1990). Increased productivity of vegetation caused by carbon fertilization (see Section 4.1) could be affecting the amount of carbon being stored in the terrestrial biosphere (Keeling et al. 1989).
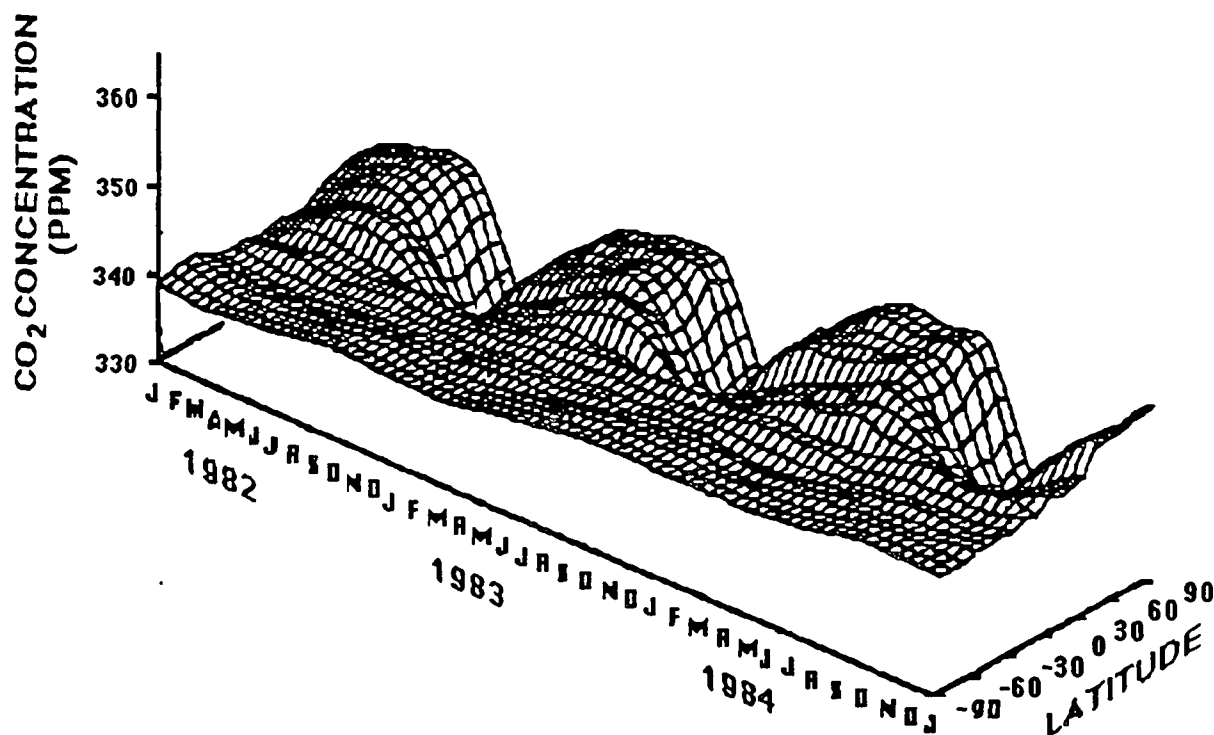
Figure 1.1-2.   Latitudinal variations in atmospheric CO_2 concentrations from 1982-1984 (adapted from Tucker et al. 1986)

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The other large uncertainty in balancing the carbon budget is the amount of carbon being released to the atmosphere through deforestation. Current estimates are about 3 Gt per year, but these estimates vary by a factor of 2-3 because of uncertainties about rates of deforestation, the amount of carbon in cleared forests, decomposition rates, and the amount of regrowth after deforestation (Dixon *in press,c*, Woodwell et al. 1983, Houghton et al. 1987, Detwiler and Hall 1988). Clearly, more research is needed to measure terrestrial carbon fluxes and to improve the understanding of the processes driving atmosphere-biosphere carbon exchanges (see recent papers by Tans et al. (1990) and Keeling et al. (1989) for a discussion of uncertainties in balancing the carbon budget and research needs).

To conclude, recent research has clearly indicated that the terrestrial biosphere is an important component of the global carbon cycle, particularly as it affects fluxes to and from the atmospheric carbon pool. Future changes in the terrestrial biosphere caused by climate change and human activities can be expected to further influence atmospheric carbon pools and thus global climate.

1.4.3 Climate Scenarios

To determine the possible impacts of global climate change on the biosphere and the resulting feedbacks to the climate system, quantitative estimates are needed of the magnitude of climate change induced by trace gases. GCMs of the earth's atmosphere are the only tool available for making quantitative estimates on a global scale of climate variables such as temperature and precipitation. GCMs are complex computer models based on fundamental principles of physics and thermodynamics (e.g., Schlesinger 1988). In the past decade, several GCMs have been used to simulate the possible effect on global climate of a doubling of CO_2 concentrations. Results of simulations of four different GCMs (listed in Table 1.4-3) are widely available for use by researchers and were used in this report to obtain the data in Sections 2 and 3. Some of the overall conclusions about future climate change and uncertainties in the GCMs are discussed in this section, as well as the general methodology for creating the future climate scenarios used in this report.

Table 1.4-3.   General Circulation Models Used to Generate Double-CO$_2$ Climate Scenarios

Model Name	Reference
Geophysical Fluid Dynamics Model (GFDL)	Manabe and Wetherald 1987
Goddard Institute for Space Studies (GISS)	Hansen et al. 1988
Oregon State University (OSU)	Schlesinger and Zhao 1989
United Kingdom Meteorological Office (UKMO)	Mitchell et al. 1989

The most recent results from the GCMs suggest that double-CO$_2$ conditions, or the radiative equivalent, will increase global temperatures by approximately 1.9 to 4.4°C (Schlesinger and Zhao 1989, Washington and Meehl 1989, Mitchell and Warilow 1987, Mitchell et al. 1989, Meehl and Washington 1990). Global precipitation could increase by 7.8% to 11% (Smith and Tirpak 1989). Regional and seasonal predictions vary more between models, sometimes differing even in the predicted direction of the change (e.g., whether precipitation increases or decreases in a region). The speed of these changes depends upon the rate of increase in CO$_2$ concentrations in the atmosphere. Current estimates suggest that CO$_2$ concentrations will double their preindustrial level of 280 ppm between the period from 2055 to 2080 if attempts are not made to stabilize emissions (Lashof and Tirpak 1989). Considering both the magnitude and rate of change, climate change induced by trace gases could be greater than any climate change that has occurred during the last 15,000 years.

Although GCMs are complicated and computationally intensive computer programs, they are far from perfect in simulating present climate (Grotch 1988, Dickinson 1989, Neilson et al. 1990). For instance, the GFDL model predicts current winter temperatures that are 1.8°C cooler than those observed for North America. The GISS model simulates current summer temperatures 3.1°C cooler than those observed for this same region. Precipitation estimates are even more problematic. Four major problems exist in how the models simulate climate: 1) poor simulation of cloud processes; 2) inadequate atmosphere-ocean coupling; 3) overly simplistic representation of the biosphere; and 4) poor spatial resolution (a common grid size is 4°x 5°) (Gates 1985, Dickinson 1986, and Schlesinger and Mitchell 1985 for additional discussion). Consequently, the accuracy of future climate simulations is considered

highly uncertain. Research efforts are underway to improve GCMs (the Department of Energy's ARM and CHAAMP programs) and to determine how well they simulate past climates as a validation technique (Cooperative Holocene Mapping Project 1988).

Despite the limitations of GCM outputs, especially their poor spatial resolution, they remain the only tool that can provide spatially distributed estimates of future climates based on the principles of atmospheric physics. The challenge for researchers estimating the effects of climate change on components of the biosphere is to use GCM output to generate reasonable scenarios of future climate for input into their models. The most common technique is to calculate the difference between (or for precipitation, the ratio of) the double-CO_2 estimate for a particular gridpoint and the control estimate (current conditions) for that same gridpoint (Parry et al. 1987, Smith and Tirpak 1989, ICF 1989). These differences are then added to (or multiplied by, in the case of ratios) the corresponding historical weather data, often the mean value for the 1951-1980 time period. For instance, if a GCM estimates that July temperatures are 2°C warmer than the control estimate for a particular gridpoint, the measured mean July temperature for a weather station in the grid box is increased by 2° to estimate future July temperatures for that particular location.

Forests historically have responded to changes in climate (Webb 1987), leaving little doubt that rapid climate change will affect forests in the future. Research to date has focused on the response of certain tree species and forest stands to climate change (e.g., Smith and Tirpak 1989). In this section, recent results concerning the potential effects of climate change on treeline, forest stands, biomes, and biodiversity are presented. In addition, a discussion of the effects of climate on belowground processes in forests from a soil carbon perspective is presented. Much of the information presented in this section forms a basis for the later analyses discussed in Sections 3 and 5.

2.1 Treeline Response

Altitudinal and latitudinal treelines are a striking and sensitive example of climate control of species distributions (Garfinkel and Brubaker 1980, Goldstein 1981, Goldstein et al. 1985, Edwards et al. 1985, Cooper 1986, Odasz 1983). Consequently, movements in treeline could be an early indicator of climate change impacts. Studying and monitoring the northern treeline is especially important since the GCM simulations of double-CO_2 climate conditions show greatest warming at high latitudes. Recently, a global network of researchers in Scandinavia, the Soviet Union, the United States, and Canada was organized to evaluate the taiga and tundra boundary response to global change (Solomon *in press*). The purpose of this section is to review our current understanding of the factors controlling treeline and to discuss possible impacts of future climate change on treeline.

2.1.1 Ecophysiological Characteristics of Treeline

Tranquillini (1979), Arno (1984), and Larsen (1989) discuss treeline characteristics ranging from general features to specific ecophysiological processes of treeline environments. Tranquillini (1979) emphasized the synergism of three closely related factors controlling alpine treeline: 1) limited dry matter production; 2) incomplete tissue maturation; and 3) inadequate climate resistance. Arno (1984) present physical and climatic factors that affect treeline position. Larsen (1989) discusses biotic communities and ecological relationships of treeline in Canada and Alaska.

Climate at high-latitude and high-altitude treelines is characterized by interactions between a short growing season, low air temperatures, frozen soils, drought stress, high levels of solar radiation, irregular snow accumulations and frequent strong winds (Ives and Hansen-Bristow 1983, Hansen-Bristow and Ives

1984, 1985). An elevational gradient (low to high) in the forest-alpine tundra ecotone is typified by a gradual decrease in tree stature, an increase in tree deformation, and a decrease in tree stand densities (Hansen-Bristow 1986). Geographically, the transition from subalpine continuous forest to alpine tundra occurs over a relatively short distance (< 2 km).

Sufficient summer heat may be the most important individual factor limiting the elevation or latitude to which trees can migrate. Treeline position ultimately depends on the increasingly unfavorable heat balance associated with rising elevation or latitude. Germination, growth, photosynthesis, and other biological processes have varying minimum temperature requirements and optimums (Tranquillini 1979). The hardiest of conifers require a growing season of two months in which no more than light frosts occur. Treelines have been correlated with the location of the 10_oC isotherm for the warmest month, usually July in the northern hemisphere. This correlation approximately holds for cold treelines throughout North America and Eurasia north of the tropics (Pearson 1931, LaMarche and Mooney 1967, Arno 1984). Thornthwaite's thermal efficiency index (Hare 1950) and Kira's warmth index (Kira 1965) have also been correlated with treeline position.

2.1.2 Treeline Response to Climate Change

An increase in temperature would shift the 10^oC isotherm northward in latitude and higher in elevation. High-latitude and high-elevation regions that were previously limited by growing season might then be able to support tree establishment and growth. One mechanism for this shift is a change in reproductive success. For example, treeline on the south slope of the Brooks Range in Alaska and isolated clusters of balsam poplar (*Populus balsamifera*) trees on the north slope commonly reproduce by vegetative means only (Edwards and Dunwiddie 1985, Lev 1987). A temperature increase may allow sufficient time for flowering to occur and for sexual reproduction to take place. Migration rates could increase substantially given that seed dispersal will occur at greater distances than branch or root vegetative propagation.

These qualitative considerations are supported by simulations of the response of global vegetation to future climate change. The simulations show a significant northward movement of the deciduous boreal forest and associated treeline in response to global warming (Emanuel 1985, Emanuel et al. 1985, Leemans 1990, Smith et al. *submitted*, Prentice and Fung *in press*).

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2.1.3 Research Needs

Treeline response to climate depends on unique local site characteristics. The challenge will be to identify the most influential and limiting factors across latitude and elevation, to determine how climate will influence these factors, and to project treeline response. There is evidence of climate moderation in the Arctic and this moderation is predicted to continue; thus, studying treeline response at high latitudes may allow a linkage between tree growth and migration rates and climate. The following research areas are suggested as providing the most direct link between treeline and climate:

1) Detection and linkage of treeline growth and migration rates to climates at high latitudes and altitudes.

2) Development of mechanistic models of tree growth in response to limiting climate conditions at high latitude and altitude treelines.

2.2 Forest Stand Effects

Stands[1] of trees and the ecosystems of which they are a part are important for social and economic reasons and for their ability to capture and retain carbon for extended periods of time (Harmon et al. 1990). It is at the stand level that effects of climate change will be most strongly felt by society and at which adaptation and mitigation efforts will be focused (see Section 5).

Considering possible effects of climate change on the composition of forest stands in the United States, Smith and Tirpak (1989) summarized modeling work completed in the Great Lakes region and southeastern United States. Dixon (in press,c) reviewed forest management planning options to cope with global change in the southern United States.

Solomon (1986) presented simulation model results for the transient response of forests in eastern North

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[1] The term "forest stand" has a clear definition in forest science. Smith (1986) states: "A stand is a contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, and condition to be a distinguishable unit. The internal structure of stands varies mainly with respect to the degree that different species and age classes are intermingled. The simplest kind of structure is exemplified by that of the pure, even-aged plantation consisting of trees of a single species. The range of complexity can extend to a wide variety of combinations of age classes and species in various vertical and horizontal arrangements."

America to CO_2-induced climate change. A distinctive dieback of extant trees was noted at most locations. The pattern of dieback and recovery varied across the region and by species. Transient responses to species composition and biomass continued for centuries after climate had stabilized.

Pastor and Post (1988) presented simulation model results for the response of northern forests to CO_2-induced climate change. The greatest changes were shown at the boreal-cool temperate forest border. The linkages between species composition, productivity, biomass, carbon and nitrogen cycles, and soil moisture were discussed. Forest productivity and biomass were directly linked to soil moisture levels. Species composition altered soil nitrogen availability which then influenced species composition. The positive feedback of the carbon and nitrogen cycles was bounded by soil moisture availability and temperature.

In this section, preliminary results are presented from a study designed to estimate the impact of climate change on forests in the Pacific Northwest. The objectives of newly initiated EPA research on the effects of climate on United States forests are summarized. Finally, the geographic scope of EPA research is broadened to discuss forest models that could be used to quantify the effects of climate change on boreal forests.

2.2.1 Pacific Northwest Forests

Preliminary modeling work on the potential response of Pacific Northwest forests to climate change was initiated as a joint research project between the EPA, the USFS Pacific Northwest Forest and Range Experiment Station, Oregon State University, and the University of Virginia. The model ZELIG (Urban and Shugart 1989) has been parameterized for the Pacific Northwest species temperature gradients and distributions[2]. The GCM scenarios for a double-CO_2 environment predict a warmer and wetter climate for the Pacific Northwest. Preliminary ZELIG model results for a period of 500 years show an upward shift of 500 to 1000 m in species distribution. For example, high-elevation forest sites would warm to resemble present-day mid- to low-elevation sites, and so on. If GCM predictions are reasonably accurate, substantial changes in forest composition can be expected in the Pacific Northwest in the next century.

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[2] ZELIG is an updated version of a class of models (known as forest gap models) that simulate tree establishment, diameter growth, and mortality on a yearly basis on a plot of defined size (Botkin et al. 1972, Shugart 1984).

2.2.2 Future Modeling of United States Forests

A joint EPA and USFS Rocky Mountain Forest and Range Experiment Station companion modeling project has been initiated to simulate the effects of climate change on Rocky Mountain tree species. The work will initially use the model FIRESUM (Keane et al. 1989), an ecological process model for fire succession in western conifer forests. The model is currently being calibrated for elevational and climate gradients and tree species in the Rocky Mountains. Preliminary model simulations predict that high-elevation sites will warm and that species composition and distribution will be altered.

The EPA is supporting work at Utah State University-Logan to develop a spatially-explicit regional scale forest simulation model with which to predict the effects of climate change on Rocky Mountain forest composition, structure, and function. At the stand level, the model will simulate the effects of climate change on reproduction, leaf area dynamics, water use, carbon/nitrogen dynamics and fire regime across a range of environments. The individual stand components will be simulated in a spatial context that allows predictions of species migration and forest fragmentation for individual regions. A set of climate change scenarios will be developed based on a regional interpretation of GCM predictions. These climate scenarios will then serve as input to the regional simulation model to predict a range of possible regional responses, each specific to a given climate scenario.

The EPA is also supporting work at the University of Florida-Gainesville to model carbon dynamics of slash pine plantations in response to climate change. The objectives are to incorporate measured slash pine physiological responses and climate change scenarios into a labile carbon model (Cropper 1987, Cropper and Ewel 1983, 1984, 1987). The research will result in simulations of the physiological and stand-level responses of slash pine plantations to potential climate change scenarios. The relative importance of respiration responses, leaf area dynamics, stand water balance, and assimilation will be assessed with the simulations.

The EPA is supporting work at the University of Montana-Missoula to couple the FOREST-BGC (BioGeoChemical Cycles; Running and Coughlan 1988) and FORET (Shugart 1984) ecosystem simulation models for projection of forest responses to global climate change. The combined model simulations will range from daily temporal scale photosynthesis-respiration balance to annual primary production to species-specific stand development over centuries. Final products are expected to include the simulation of forest production, succession, growth, and development for a western coniferous forest and an eastern deciduous forest over a 200-year period. Simulations will first be done for current climate conditions over a range of sites and disturbance conditions, and then with either a transient or a

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fixed double-CO_2 climate change scenario. Shifts in primary production, recruitment-mortality, and species migration will be tracked. Relative differences in response of western coniferous and eastern deciduous forests will also be emphasized.

Prentice et al. (1989) describe the development of a global vegetation dynamics model. The modeling approach is to generate vegetation dynamics on a small patch for several climate scenarios. The scenario projections represent a range of spatial distributions of environmental variables among patches within landscapes. Mean values of environmental variables can then be interpolated using existing global environmental databases. The modeling approach allows a linkage between small-scale vegetation process and global scale atmospheric processes, making full use of existing environmental data. The range of scales also allows natural and anthropogenic disturbances to be incorporated into predictions.

2.2.3 Boreal Forests

Boreal forests are important components of the terrestrial biosphere, and their feedbacks and responses to global changes will be significant (Dixon *in press,a*). Bonan and Shugart (1989) present a unifying model that links the structure, function, and pattern of boreal forest vegetation with environmental factors that interact and account for the pattern of boreal forest types and productivity: climate, solar radiation, soil moisture and the presence of permafrost, the forest floor organic layer, nutrient availability, insect outbreaks, and wildfires. Bonan (1989) discusses a computer model to predict regional patterns of soil radiation, soil moisture, and soil thermal regimes in boreal forests in North America, Scandinavia, and the Soviet Union. Environmental factors are calculated on a monthly time step, a temporal scale suitable for use in models of forest succession. The ecological consequences of climate change for environmental factors can then be explored.

Two gap models based on individual trees have been developed for the boreal forest region: LOKI for North American boreal forests (Bonan 1988), and FORSKA for the Scandinavian boreal forests (Leemans and Prentice 1989). A general boreal forest simulator has been developed by combining FORSKA and LOKI at the University of Virginia in collaboration with Bonan and Leemans. The EPA is supporting work to use this simulator to generate baseline boreal forest dynamics as well as transient departures under climate change scenarios.

2.2.4 Research Needs

Research should link detection of tree and stand response (extensive research sites) to mechanisms of tree and stand response (intensive research sites) and to climate change disturbance. Once mechanisms of forest response are identified and modeled, climate change scenarios from GCMs can be used to predict vegetation response over transient and equilibrium conditions. Research projects currently funded by the EPA and the following suggested research will help make the linkages necessary to achieve these goals:

o   A pole-to-pole transect of extensive and intensive research sites at ecotonal boundaries, especially high-altitude areas, to provide local, regional, and global data on species interaction and on factors limiting species distribution at the stand level for a wide range of species.

2.3   Carbon Sequestration in Soils

Globally, soils contain the largest non-fossil, terrestrial reservoir of carbon (see Figure 1.1-1). The soil reservoir is estimated to contain between 1170 and 1740 Gt of organic carbon (Bolin 1983, Schlesinger 1984, Houghton and Woodwell 1989, and Schneider 1989b); that may be three times the amount of carbon stored in vegetation and twice the amount of carbon currently in the atmosphere.

Soils have been often overlooked as a component of the global carbon cycle. Soils, as a carbon pool, were not considered in 1989 EPA Report to Congress (Smith and Tirpak 1989). A number of studies have shown that the clearing of forests for agriculture has resulted in declines in soil organic matter (Giddens 1957, Paul 1976, Mann 1986). The amount and rate of decline in soil organic matter are a function of a number of factors other than forest clearing per se (Allen 1985, Oades 1988). However, such declines demonstrate the lability of soil carbon and have raised the question of how losses in organic matter relate to CO_2 releases to the atmosphere. The role of soils in relation to global change is receiving increased attention not only because of the size of the soil carbon pool that could become a net source of atmospheric CO_2, but because soils also represent a potential sink for carbon (Greenland and Nye 1959, Jenkinson and Rayner 1977, Armentano and Ralston 1980, Lugo and Brown 1986).

The purpose of this section is to: 1) summarize the importance of forest soils in the global carbon cycle; 2) present a heuristic model of soil carbon dynamics; 3) identify and discuss factors that affect the size of the soil carbon pool; and 4) assess the potential effects of increasing CO_2 and climate change on this

reservoir of carbon. In Section 5.2, the management of soils for the purpose of storing carbon is reviewed and discussed.

2.3.1 Forest Soils and the Global Carbon Cycle

Terrestrial photosynthesis removes approximately 110 Gt of carbon from the atmosphere annually, only a portion of which is retained in the annual increment of aboveground biomass (Oades 1988, Schneider 1989b). Nearly half of this carbon is returned to the atmosphere through direct plant respiration, and the other half is deposited on or in the soil. While this carbon is being incorporated into the soil, an equivalent amount is returned to the atmosphere from the soil via oxidation of organic matter to CO_2 At steady state, the amount of carbon fixed (110 Gt) is equal to the amount released (110 Gt) by respiration and decomposition (Figures 1.1-1 and 2.3-1).

In an undisturbed world, climate and soils are the principal factors controlling the distribution and productivity of forests. These two variables also control the amount of carbon stored in forest ecosystems. Boreal, temperate, and tropical forests cover approximately one-third of the earth's land surface (Table 2.3-1, Waring and Schlesinger 1985). Combined, these three forest biomes contain approximately 743 Gt of carbon, or 90% of the aboveground carbon stored in biomass. Belowground, they contain approximately 576 Gt of carbon, or about 40% of the carbon sequestered in soils.

Allometric relationships between aboveground and belowground carbon productivity in forests have been proposed (Newbould 1967), but are not universally accepted (Böhm 1979). Rather, the observed relationships are often a function of environmental conditions. For example, the data in Table 3.1-2 suggest that total belowground carbon pools are at least equal to total aboveground carbon pools and, in some cases, are 40-fold greater than aboveground carbon pools.

Because of warmer climates (given similar moisture regimes), tropical forests are more productive than temperate and boreal forests. At the same time, they have greater decomposition rates and less belowground relative to aboveground storage (Table 3.1-2). In boreal systems the converse is true. Temperate forests are intermediate. Additionally, tropical forest soils have low carbon:nitrogen (C:N) ratios, whereas boreal forest soils have high C:N ratios (Post et al. 1985). The C:N ratio is a good indicator of the extent of decomposition (low ratios indicate more readily decomposable materials).

Table 2.3-1. Biomass and Soil Carbon in Boreal, Tropical, and Temperate Forest Ecosystems
(from Waring and Schlesinger 1985)

Forest Ecosystem	Area $(10^6 km^2)$	Total Biomass (Gt)	Total Soil Carbon (Gt)
Tropical	24.5	460	255
Temperate	12	175	142
Boreal	12	108	179
Total	48.5	743	576
World Totals	147	827	1456

With increased greenhouse gases in the atmosphere and the potential for changes in global climate, as well as the demands of an increasing world population, the balance between fixed and released carbon may be altered. This may result in changes in the large stocks of above- and belowground carbon in forest systems and ultimately in the concentration of CO_2 in the atmosphere. These changes in atmospheric CO_2 in turn are likely to lead to additional redistribution of forests, with an accompanying change in the amount of carbon stored in forest ecosystems in both the above- and belowground pools.

2.3.2 Soil Carbon Dynamics: A Conceptual Model

Soil organic matter can be divided into two principal components: a living component and a nonliving, or dead, component (Theng et al. 1989). The living fraction includes plant roots and macro- and microorganisms. This fraction usually constitutes less than 4% of the total amount of soil organic matter (Theng et al. 1989). The remaining 96-98% of soil organic matter is nonliving and is divided between macro-organic matter and humus. Macro-organic matter includes plant residues that are in various stages of decomposition but that are larger than 0.25 mm. Humus is simply the organic material remaining after the removal of the macro-organic matter.

Figure 2.3-1 depicts a conceptual model of the pools and fluxes of carbon in terrestrial ecosystems. The boxes represent pools and the arrows represent the flux of carbon between pools and the direction of carbon flow. In this model, carbon is divided into living and nonliving pools. The model distinguishes

between aboveground and belowground pools and fluxes. Such a model is broadly applicable across temporal and spatial scales, and it can be an important heuristic in developing a better understanding of the terrestrial carbon cycle. It is also useful for identifying areas of uncertainty that need research and quantification.

Five carbon pools are presented in the conceptual model. Pool C_1 refers to the aboveground living portion of vegetation. Pool C_2 is the belowground component of vegetation, including coarse and fine roots. C_2 also includes living macro- and microorganisms. On the nonliving or detrital side of the model is the aboveground pool, C_3, which is the pool of organic litter or detritus. Belowground are pools C_4 and C_5. Pool C_4 is the fraction of soil carbon that is readily accessible for decomposition (also called the "labile" pool). Pool C_5 represents that portion of the soil that is protected, either chemically or physically, from decomposition.

Fluxes:

F1 = gross photosynthesis
F2 = above-ground respiration
F3 = litter deposition
F4 = below-ground transport
F5 = rhizosphere respiration
F6 = rhizo-deposition + exudates
F7 = litter incorporation + leaching
F8 = litter respiration
F9 = soil organic matter respiration
F10 = leaching and erosion
F11 = chemical and physical fixation
F12 = chemical and physical release

O.M. = Organic Matter

C_n's = Terrestrial Carbon Pools

Change in pool size:

$$\Delta C_n = \Sigma \text{ influxes} - \Sigma \text{ effluxes}$$

$$= (C_n) \, t1 - (C_n) \, t2$$

Where: ΔC_n = the change in the size of the nth carbon poo

t1 = time one, t2 = time two

Figure 2.3-1.   Simplified conceptual model of carbon pools and fluxes in terrestrial ecosystems.

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The conceptual model identifies 12 distinct pathways for carbon to flow between pools or out of the system, each of which represents the combination of several processes: Flux F1 represents the fixation of CO_2 (gross photosynthesis). The arrows pointing up and away from boxes or pools (F2, F5, F8, and F9) represent losses through either autotrophic or heterotrophic respiration. Flux F3 represents litter deposition at the soil surface. Flux F4 represents the shoot-to-root transport of carbon-based materials. Flux F6 represents root and microbial biomass turnover. Flux F7 represents the incorporation of litter into the soil, which occurs either by a physical mixing process or by leaching. Flux F10 is the loss of carbon through leaching, including organics and bicarbonate. Flux F11 represents chemical and physical fixation or protection, and F12 represents release by either chemical or physical protection.

Equation 2.3-1 can be used to evaluate the dynamics of the terrestrial carbon cycle, and, in particular, of individual carbon pools. Equation 2.3-2 represents an alternate method for determining ΔC_n.

$$\Delta C_n = \Sigma \text{ influxes } - \Sigma \text{ effluxes} \qquad (2.3-1)$$

$$= (C_n)_{t2} - (C^n)_{t1} \qquad (2.3-2)$$

where: ΔC_n = the change in the size of nth carbon pool

$t1$ = time 1

$t2$ = time 2

The usefulness of Equation 2.3-1 is based upon the ability to measure or determine the magnitude of all of the carbon fluxes acting on a particular carbon pool. It is not necessary to know the actual size of the pool to determine ΔC_n if all the fluxes can be quantified. Direct measurement of ΔC_n may facilitate quantification of one or more carbon fluxes. When ΔC_n is equal to zero, the respective carbon pool (i.e., no net change in C_n), is at steady state; carbon inputs to the pool are therefore equal to carbon outputs. When ΔC_n is positive, net productivity of the pool is positive and the pool is a sink for carbon. Conversely, when ΔC_n is negative, net pool productivity is negative, and the pool is a source of carbon.

It would be useful to have measures of ΔC_n for each of the pools of terrestrial carbon to evaluate the sink/source performance of the whole system and to model terrestrial carbon dynamics. Obtaining accurate measures of aboveground carbon pools is difficult due to the heterogeneity of individual stands. Likewise, accurate measures of belowground pools of carbon are difficult to make, as are the flux measures. Techniques for measuring carbon fluxes and belowground pools must be improved or new methods developed because current methods lack accuracy and specificity. When accurate measures are available, experiments can be conducted to evaluate more conclusively the effects of

internal and external factors on the fluxes of carbon, which will lead to a better understanding of the potential effects of global change on terrestrial carbon dynamics. In the following section, the factors that affect carbon flux are discussed.

2.3.3 Factors Affecting the Accumulation of Soil Carbon

The accumulation and distribution of soil organic matter (carbon) depend primarily on the quality and quantity of organic inputs and the rates of microbially mediated decomposition (Oades 1988). They also depend upon the extent to which the soil protects some fraction of the organic material from decomposition (Oades 1988, Duxbury et al. 1989). The sequestration of carbon in soils is complex and depends on both biotic and abiotic factors, including: 1) edaphic factors; 2) precipitation; 3) biology; 4) temperature; 5) solar radiation; 6) time; 7) landscape factors; 8) history; 9) management; and 10) atmospheric factors. The rationale for each factor is as follows:

1)   Edaphic factors include soil physical and chemical properties, such as soil nutrient status, pH, particle size distribution, clay mineralogy, bulk density, and water holding capacity.

2)   Precipitation includes the amount and timing of rainfall, snowfall, etc.

3)   Biology includes the vegetation that fixes carbon through photosynthesis and the belowground plant parts that acquire water and nutrient resources. It includes the physiology of growth and the habit of rooting. It also includes soil biology; that is, the suite of organic matter reducers and decomposers that ultimately lead to the oxidization of a portion of the fixed carbon.

4)   Temperature includes both the aboveground and belowground temperature. The aboveground temperature affects primary productivity; the belowground temperature affects the rates of decomposition.

5)   Solar radiation refers to the amount and duration of photosynthetically active radiation (PAR), which is the light required to drive photosynthesis. Annual PAR is determined to a large extent by latitude. Other factors, such as air pollution, water vapor, and cloud cover, also affect the amount of PAR. At the highest latitudes, insufficient PAR may limit primary production.

6)   Time is important because soil carbon accumulates over long periods of time. Consequently,

the time since a disturbance (e.g., fire, harvest) will influence the amount of carbon that accumulates in soil.

7)   Landscape features such as aspect, slope, landscape position (e.g., toe slope, bottom), and shape (convex versus concave) affect the mass movement of soil materials and the hydrologic routing of soil water. Consequently, these factors affect the accumulation of soil organic matter.

8)   History includes the effects of past disturbances that affect the accumulation of soil carbon, such as fire, pests, flooding, mass wasting, glaciers, etc.

9)   Management could also be called land use, mismanagement, or non-natural disturbance. It refers to effects due to human influence. Examples include conversion of forests to agriculture, deforestation, urbanization, road building, etc.

10)   Atmospheric chemistry refers to the composition of the gaseous atmosphere in which vegetation is growing. There is evidence that increased levels of ozone (Sharpe et al. 1989) and CO_2 (Norby et al. 1987) affect the allocation of carbon from shoots to roots.

No attempt has been made here to present quantitative relationships between these factors and the accumulation of carbon in soils. In fact, many of the relationships are only qualitative at this point. The relationships that are reported in the literature are usually for single factors, not for several interacting factors. However, some quantitative bivariate relationships have been reported, such as the positive correlation between soil clay content and the stabilization of soil organic matter (Oades 1988). The primary purpose for taking a heuristic approach is to emphasize the complexity of soils and to identify the relevant influences on the storage of carbon in soils.

2.3.4   Potential Effects of Global Change on Carbon Storage in Soils

Because the extent and magnitude of global climate change is uncertain, the effects of such a change on carbon storage in forest soils are even more uncertain. It is possible, however, to speculate on the likely effects based upon potential climate change scenarios and known or expected relationships between soil carbon and the factors that influence it. Some factors will not be affected by climate change (e.g., soil clay content), but they may affect the amount of carbon stored in soil.

If mean annual air temperatures increase, with all other factors constant, ecosystem productivity will probably increase and the amount of carbon fixed will increase. At the same time, however, decomposition rates will be amplified. The net result is likely to be a reduction in the amount of carbon stored in the soil. Tundra and boreal soils are likely to be particularly sensitive to warming. If temperatures are elevated and precipitation is reduced, the negative effect on soil carbon will be exacerbated to a point. As long as the soils are moist enough to meet microbial needs, decomposition will proceed. If the systems get too dry, decomposition will decrease significantly. Concomitantly, primary production will decrease. If precipitation increases along with soil temperature, the amount of carbon stored in soils is likely to increase because decomposition of soil organic matter is reduced in very wet soils (Ino and Monsi 1969, Oades 1988).

One potential cumulative effect of climate change is the shifting of the areal extent and distribution of biomes. This will affect the storage of carbon in soils. Shifts from forests to grassland may lead to more carbon being stored belowground, but much less stored in aboveground biomass. Using the data of Waring and Schlesinger (1985), mean biomass for temperate forests and temperate grasslands are 15 and 1 kg carbon/m^2, respectively. Mean soil carbon for these two systems are 11.8 and 19.2 kg carbon/m^2, respectively. A shift from temperate forests to temperate grasslands would result in a change in mean ecosystem carbon from 26.8 to 20.2 kg carbon/m^2. The result is a net loss of carbon to the atmosphere, but a net increase in belowground carbon. A shift from temperate grasslands to forests would have the equal but opposite effect, and it is a possibility. A detailed discussion of such analyses is presented in Section 3.1.

As a result of the direct effect of elevated CO_2 on vegetation, global change might indirectly affect soil carbon storage. As mentioned previously, elevated CO_2 has been shown in some circumstances to increase the allocation of carbon from shoots to roots (Norby et al. 1987), primarily because of a fertilizer-like effect of CO_2 on plant growth. In response, plants allocate more carbon to build more extensive root systems necessary for acquiring additional resources (e.g., water, nutrients). The allocation of additional carbon belowground could lead to increased levels of carbon sequestering in soils.

2.3.5 Research Needs

The storage of carbon in soils is a very complex process that is not fully characterized or understood. To develop strategies to mitigate global change, including strategies to manage the biosphere, the carbon cycle must be more fully understood. In addition, a number of other areas related to terrestrial

carbon dynamics require more research. One purpose of current analyses at ERL-C is to characterize the terrestrial carbon cycle and then to project the long-term effects of increasing CO_2 and changing climates on terrestrial carbon pools and fluxes. In that light, work is needed in the following areas:

1) Quantification of carbon pools and fluxes in specific ecosystems under ambient or steady state conditions to develop general principles from the specific examples.

2) Characterization and quantification of the factors that control carbon fluxes.

3) Development of methods to characterize the pools and lability of soil organic matter so that these measures can be related to dynamic and biologically relevant processes.

4) Quantification of the effects of land use and management on soil carbon.

5) Characterization and quantification of the stabilization of soil organic matter by abiotic soil factors.

6) Development of simulation models that accurately project how carbon fluxes (and thus pools and feedbacks to the atmosphere) will shift in specific ecosystems under a series of altered climate scenarios.

2.4   Effects of Global Climate Change on Global Vegetation

As described in Section 1.4.2, changes in fluxes of carbon to the atmosphere from the terrestrial biosphere can significantly affect atmospheric CO_2 concentrations. Projected changes in global climate (Section 1.4.3) could result in a significant redistribution of global vegetation, resulting in large changes in carbon pools and fluxes. These changes could provide significant positive or negative feedbacks to climate change.

To begin an evaluation of the potential significance of this feedback phenomenon, the current best estimates of changes in global vegetation caused by climate change are summarized here. The data presented in this section form a basis for calculating changes in terrestrial carbon storage in Section 3.

2.4.1 Global Vegetation Models

Several models describing the global distribution of vegetation (or at least classification schemes relating climate to vegetation) are available with which to estimate the redistribution of vegetation in response to climate change. These include models of Holdridge (1947, 1967), Köppen (1900, 1918, 1936), Box (1981), and Lashof (1987). Tuhkanen (1980) and Prentice (1990) have reviewed these models. The original Holdridge (1947, 1967), modified Holdridge (Prentice 1990), Box (1981), and Lashof (1987) approaches have been used to predict the redistribution of vegetation in response to climate change.

The Holdridge life zone classification uses three climate parameters to define the occurrence of major plant formations: biotemperature, mean annual precipitation, and a potential evapotranspiration (PET) ratio. Biotemperature is a temperature sum over the course of a year, with unit values (e.g., daily values) that are less than 0°C set to 0°C. PET, as Holdridge (1967) defined it, is a linear function of biotemperature, and thus it does not add degrees of freedom to the model. The PET ratio is defined as PET/mean annual precipitation. Thus, the Holdridge classification system is really only based on two climate variables, biotemperature and total annual precipitation. Holdridge created an axis system using these climate parameters to classify life zones (Figure 2.4-1). Mean annual precipitation forms two axes of an equilateral triangle, with the third being the PET ratio. Annual biotemperature forms a separate axis perpendicular to the base of the triangle. The Holdridge classification thus creates hexagons that define specific life zones.

Figure 2.4-1. Holdridge life zone classification system (Holdridge 1967).

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A significant factor in evaluating simulations of future vegetation patterns is understanding how well the vegetation model simulates current vegetation patterns. The Holdridge life zone classification reproduces broad-scale global vegetation patterns (Leemans 1990), but it is inaccurate for many regions of the world (only vegetation in 40% of 1°x 1°gridboxes are correctly simulated by the Holdridge system (Prentice 1990)). Prentice (1990) evaluated and refined the Holdridge system to improve its accuracy. In the initial simulation, in which climate space was divided on a finer scale than in the original Holdridge classification, vegetation in 58% of the land gridboxes was correctly simulated. An additional refinement was to aggregate observed vegetation units based on similarity of vegetation and climate. For the final analysis, 18 primary vegetation types and 11 transitional zones were defined. Using this scheme, vegetation in 77% of the gridboxes was predicted correctly.

A more complicated but more biologically realistic global vegetation model was developed by Box (1981). Instead of analyzing climate-biome relationships, Box analyzed the distributions of 77 plant life forms (e.g., summergreen broadleaved trees) throughout the world. For each life form, a set of eight different climate values were correlated with the range limits of the life form. In essence, Box created a set of 77 different climate envelopes within which the life form occurs and outside of which the life form is absent. The Box model can predict combinations of growth forms at any given location, so it is capable of predicting canopy structure.

Box evaluated his model by simulating life forms present at 74 sites around the world. The actual dominant growth forms were predicted for 92% of the sites, but all dominants and codominants, and no others, were correctly predicted for only 50% of the sites.

Lashof (1987) developed a statistical model of climate-vegetation relationships using Olson et al.'s (1983) vegetation database. Since this database reflects actual rather than potential vegetation, the Lashof model is the only currently available approach that incorporates land use.

2.4.1.1 Limitations of Global Vegetation Models

The four global vegetation models just summarized have significant limitations for predicting future global vegetation patterns. First and foremost, all are steady-state models and are non-dynamic. They give no information on how long it would take the vegetation to return to an equilibrium with climate. It may take 200-500 years for forest and shrub species to respond to a large climate change (Davis et al. 1986, Webb 1986). Thus, these models cannot be used directly to estimate vegetation patterns that could exist in the next century. Second, the Holdridge and Lashof approaches, and to a lesser degree

the Box approach, are based on empirical relationships between climate and vegetation. Since future climate regimes in some regions may be different from any present in the world today, vegetation models based on the mechanistic response of species or growth forms to climate must be developed. Third, the models are imperfect predictors of present vegetation, which introduces bias into the simulations of future vegetation patterns. Fourth, none of the models take into account the effect of soils (e.g., nutrient availability, texture) or land use (with the exception of the Lashof model) on vegetation distribution. Thus, simulating future vegetation using these models assumes that there are appropriate changes in soils to support the predicted vegetation type. In regions where soils have a major effect on vegetation cover, predictions by the vegetation models will likely be incorrect. Fifth, the direct effects of CO_2 on plants are not incorporated into the models.

2.4.2 Equilibrium Simulations of Future Vegetation Patterns

Despite the limitations discussed above, simulations of the potential response of vegetation to future climate change are useful for understanding both the magnitude of possible vegetation change and biospheric feedbacks to climate change. Several global simulations have been recently completed that form the basis for estimating changes in carbon pools and fluxes. Emanuel (1985) and Emanuel et al. (1985) made the first global projection of future vegetation patterns using the Holdridge approach, although only changes in temperature were used to calculate future vegetation patterns. A more recent and complete simulation using the Holdridge approach and five climate scenarios has been completed by Leemans (1990) and Smith et al. (*submitted*). Prentice and Fung (*in press*) used the refined Holdridge system (Prentice 1990) to project future vegetation patterns and carbon storage. Smith et al. (*submitted*) also used the Box model to project changes in vegetation in the tropical and boreal regions of the world.

Major changes in the distribution of the world's vegetation are projected under all the double-CO_2 climate scenarios and the different vegetation models (Emanuel 1985, Emanuel et al. 1985, Smith et al. *submitted*, Prentice and Fung *in press*). The results of each analysis are briefly summarized here. It should be emphasized that these analyses are for potential natural vegetation and do not take into account human land usage (e.g., agriculture).

Emanuel (1985) and Emanuel et al. (1985) created a future climate scenario using temperature data from Manabe and Stouffer's (1980) simulation of global climate under quadruple-CO_2 concentrations. Temperature changes were divided by two to create a double-CO_2 climate scenario. Under this scenario, tropical forests, grasslands, subtropical deserts, and boreal deserts showed significant

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expansion, whereas subtropical forests, boreal forests, warm temperate forests, tundra, and ice contracted significantly (Table 2.4-1).

Table 2.4-1.   Changes in Global Vegetation Distribution in a Double-CO $_2$ Atmosphere using the Holdridge Classification System (as applied by Emanuel 1985 and Emanuel et al. 1985)

Vegetation Type	Current Area (10^6 km^2)	Double-CO$_2$ Area (10^6 km^2)	Percent Change
Ice	2.22	0.57	-74
Tundra	4.47	3.03	-32
Boreal Deserts	1.31	2.59	98
Boreal Forests	17.26	10.88	-37
Cool Temperate Deserts	4.84	4.04	-16
Grasslands	22.78	28.52	25
Cool Temperate Forests	11.29	11.63	3
Warm Temperate Deserts	6.75	5.41	20
Warm Temperate Forests	15.81	14.69	- 7
Subtropical Deserts	2.91	3.66	26
Tropical Deserts	10.74	12.63	18
Subtropical Forests	11.96	9.38	-22
Tropical Forests	19.03	24.33	28
Total	131.37	131.36	

Smith et al. (submitted) used five different climate scenarios generated from output from the four GCMs described in Section 1.4.2. The fifth scenario is a second run of the GFDL model using a more realistic heat flux, and it is referred to here as GFDL-QFlux. Under all climate scenarios, the tundra, cold parklands, forest tundra, boreal forest, cool desert, warm temperate forest, and tropical seasonal forest biomes generally decreased significantly in areal extent (Table 2.4-2). The temperate forest, tropical semi-arid, tropical dry forest, and tropical rain forest biomes increased in areal extent. Tropical rain forests doubled in area under the GISS and OSU climate scenarios. The GFDL-Qflux scenario results represent the least change from the present, with only the cold parklands and tropical rain forests changing in size by more than 20%.

Table 2.4-2.   Changes in Global Potential Vegetation Distribution in a Double-CO$_2$ Atmosphere using the Holdridge Classification System (as applied by Smith et al. submitted)

Biome	Current Area (10^{6}km^2)	GFDL	GFDL-QFlx	Percentage Change GISS	OSU	UKMO
Tundra	9.30	-66	- 9	-54	-49	-69
Cold Parklands	2.79	1	-28	-15	- 4	-39
Forest Tundra	8.90	-56	- 1	-34	-33	-62
Boreal Forest	15.03	-36	3	-10	- 6	-32
Cool Desert	4.01	-24	-13	-42	-21	-48
Steppe	7.39	57	-10	- 6	18	- 3
Temperate Forest	9.94	19	17	35	16	31
Hot Desert	20.85	- 1	- 4	-15	- 7	- 4
Chaparral	5.58	33	- 3	- 2	-12	54
Warm Temperate Forest	3.17	-38	7	-40	-23	- 9
Tropical Semi-Arid	9.56	46	-10	75	27	74
Tropical Dry Forest	14.86	32	- 5	30	0	75
Tropical Seasonal Forest	15.13	-34	- 5	-48	-33	-49
Tropical Rain Forest	8.46	82	47	105	137	52
Total	134.97					

Prentice and Fung (in press), using a GISS climate scenario, also reported significant increases in the areal extent of tropical rain forests, as well as savanna, cold deciduous broadleaved forest and woodland, and drought deciduous forest (Table 2.4-3). Drought deciduous woodland, arid grassland, desert, evergreen needle-leaved forest, tundra, and temperate evergreen seasonal forest all showed significant decreases in area.

Table 2.4-3. Changes in Global Vegetation Distribution in a Double-CO$_2$ Atmosphere using the Holdridge Classification System (as modified by Prentice 1990 and applied by Prentice and Fung *in press*)

Vegetation Type	Area (10^6 km^2)	Percent Change	Double-CO$_2$ Area
Polar Desert and Ice	3.00	0	3.00
Tundra	7.00	- 63	2.59
Cold-Deciduous Needleleaved Forest and Woodland	16.00	5	16.80
Evergreen Needleleaved Forest and Woodland	6.00	- 66	2.04
Mesic Grassland	2.00	- 17	1.66
Drought-Deciduous Woodland	6.00	- 42	3.48
Arid Grassland and Shrubland	30.00	- 22	23.40
Cold-Deciduous Broadleaved Forest and Woodland	12.00	40	16.80
Temperate Evergreen Seasonal Broadleaved Forest	2.00	- 31	1.38
Mediterranean Forest and Woodland	2.00	4	2.08
Desert	14.00	- 62	5.32
Savanna	5.00	35	6.75
Drought-Deciduous, Drought-Seasonal Broadleaved Forest	9.00	21	10.89
Tropical Rain Forest	19.00	75	33.25
Total	133.00	129.44	

In contrast to the results using the Holdridge system presented, preliminary estimates using the Box approach suggest that tropical forests will decrease in area rather than increase (Smith *personal communication*).

To compare the results of Emanuel (1985), Emanuel et al. (1985), Smith et al. (*submitted*), and Prentice and Fung (*in press*), the vegetation classes they used have been grouped into six broad vegetation types (Table 2.4-4, Figure 2.4-2). Generally, there is agreement in terms of the sign of the predicted vegetation change. Deserts, boreal forests, and tundra types decreased in areal extent, whereas grasslands, temperate forests, and tropical forests generally increased in area under double-CO$_2$ climates. Across the seven different simulations and six vegetation categories, there are only four differences in the direction of the predicted change. The GFDL-Qflux climate scenario caused the

smallest changes in global vegetation. Despite the general agreement in the sign of the changes, there are significant differences in the estimated magnitude of the vegetation changes. For instance, estimates of the future distribution of boreal forest differ by a factor of two.

Table 2.4-4. Comparison of Global Vegetation Distribution in a Double-CO $_2$ Atmosphere using the Holdridge Classification System, as applied by Three Teams of Investigators

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Smith et al. (*submitted*) Predictions

Vegetation Type	Current Area (10⁶ km³)	GFDL	Percentage Change GFDL-QFlx	GISS	OSU	UKMO
Deserts	20.80	- 1	- 4	-15	- 7	- 4
Grasslands/Shrubland	26.60	35	- 9	18	9	30
Temperate Forests	13.10	5	14	17	7	21
Boreal Forests	26.70	-39	- 2	-19	-15	-43
Tropical Forests	38.50	17	6	16	17	21
Tundra	9.30	-66	- 9	-54	-49	-69
Total	135.00					

Prentice and Fung (*in press*) Predictions

Vegetation Type	Current Area (10⁶ km³)	Percentage Change (GISS)
Deserts	14.00	- 62
Grasslands/Shrubland	38.00	- 25
Temperate Forests	16.00	27
Boreal Forests	22.00	- 14
Tropical Forests	33.00	54
Tundra	10.00	- 44
Total	133.00	

Emanuel et al. (1985) Predictions

Vegetation Type	Current Area (10⁶ km³)	Percentage Change
Desert	20.40	6
Grasslands	27.62	18
Temperate Forests	27.10	- 3
Boreal Forests	18.57	- 27
Tropical Forests	30.99	9
Tundra	6.69	- 46
Total	131.37	
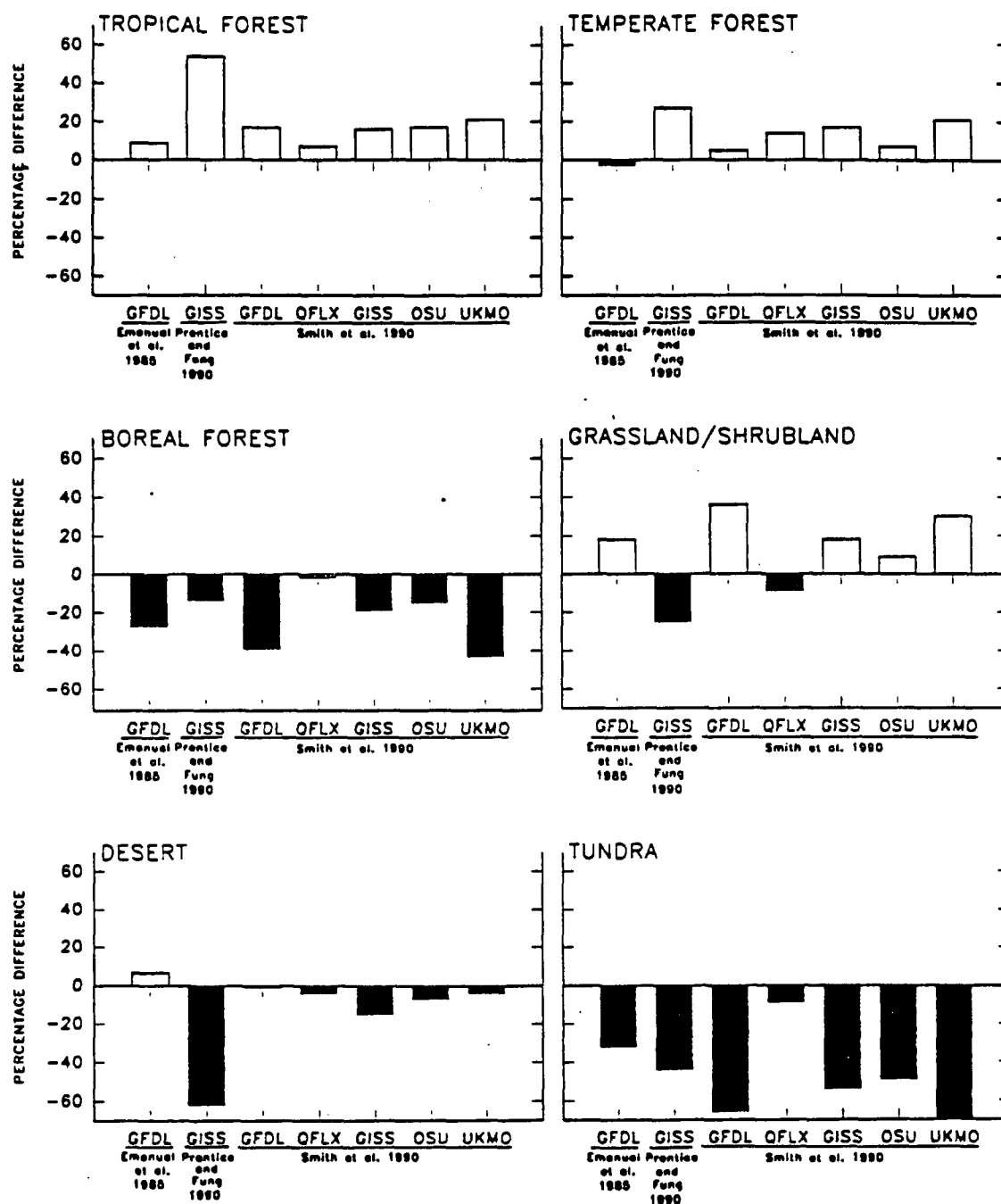
Figure 2.4-2.   Histograms showing changes in the total area of six major vegetation types after a double-CO$_2$ induced climate change. Data are also summarized in Table 2.4-4.

The results presented here in effect are summaries of global vegetation before and after a climate change caused by a doubling of CO_2 concentrations. What is not indicated by these numbers is the amount of land predicted to change from one vegetation type to another. This could significantly impact the global carbon cycle because of the transient release of carbon to the atmosphere from vegetation dieback (see Section 3.2). In the Prentice and Fung (*in press*) scenario, 60% of the vegetated landscape on the globe changed vegetation type. In the Smith et al. (*submitted*) scenarios, 16% (GFDL-QFlux) to 56% (UKMO) of the earth's land surface changed vegetation type (Table 2.4-5, Figure 2.4-3). Such predicted changes would have significant impacts on biodiversity (discussed in the next section), water resources, forest resources, agriculture, and land management.

Table 2.4-5.   Areal Extent of Land on the Globe Changing Vegetation Cover under Double-CO $_2$ Conditions as Estimated Using the Holdridge system (Smith et al.*submitted*)

Climate Model	Amount of Land Changing Vegetation Cover (10^6 km^2)	Percent of Land Surface Changing
GFDL	65.24	48.34
GFDL-QFlux	21.51	15.94
GISS	60.36	44.72
OSU	53.73	39.81
UKMO	76.21	56.46
(Total Land Area:	134.97)	

A
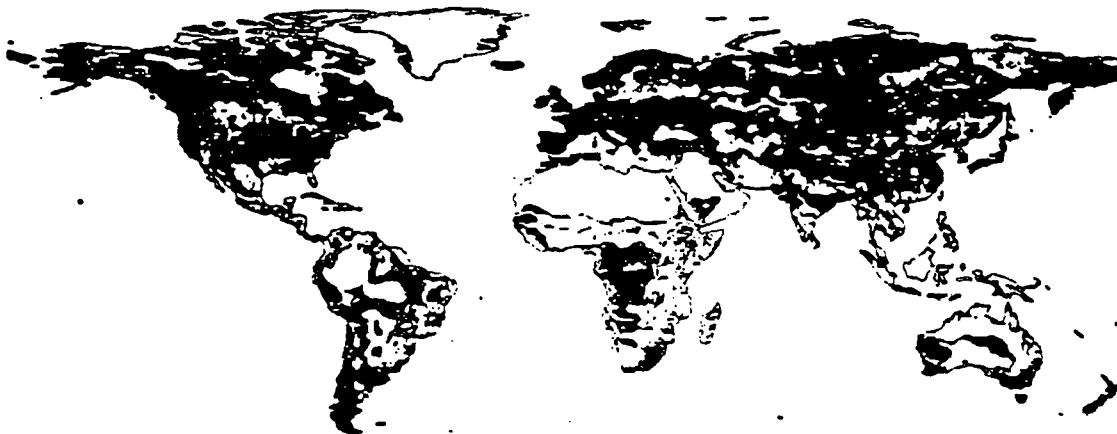
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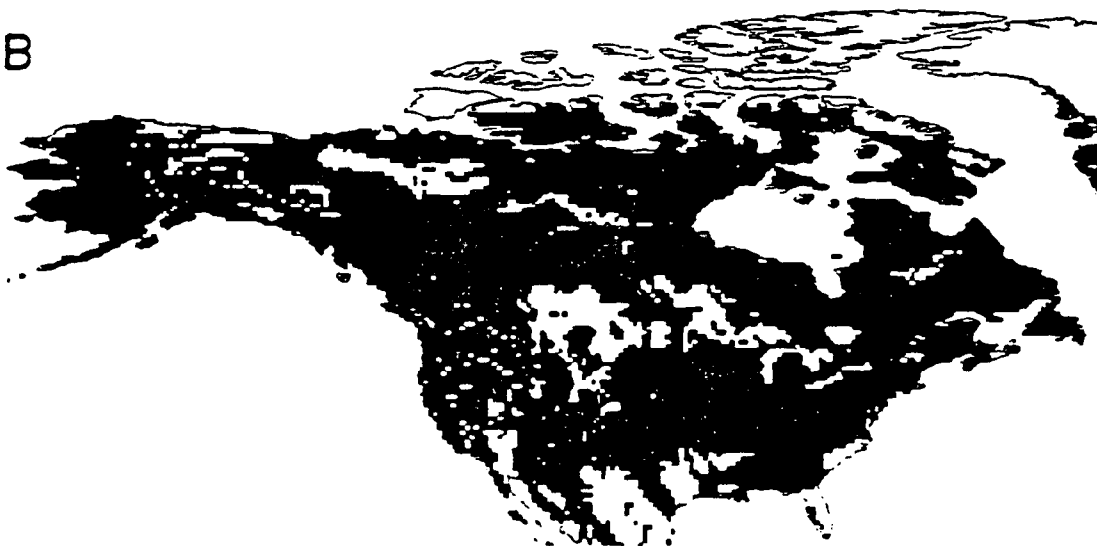
Figure 2.4-3. a) Global and b) North American areas (shaded) in which predicted future vegetation is different from current vegetation using the UKMO double-CO_2 climate scenario (Smith et al. submitted).

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2.4.3 Discussion of Vegetation Scenario Results

The fact that the vegetation scenarios are similar (in terms of the sign of the change) using the Holdridge approach is not surprising, given that the GCM scenarios on a global basis predict warmer and wetter conditions than exist at present (see Section 1.4.3). In general, a point in a given climate space on the Holdridge diagram (Figure 2.4-1) can be expected to move down and to the right under double-CO_2 climate conditions. More detailed results from Smith et al. (*submitted*) not presented here in fact show that this is often the case. For instance, areas of current tundra vegetation are estimated to change to forest tundra or boreal forest in the future. Tropical seasonal forest regions that change type tend to change to tropical rain forest.

Estimates of current area of the six vegetation types can differ substantially between investigators. That the Prentice and Fung (*in press*) areas are different is not surprising, as they used a different vegetation classification system from the original Holdridge system. However, Emanuel (1985), Emanuel et al. (1985), and Smith et al. (*submitted*) used the same basic vegetation units in their analyses, and they aggregated the units in the same way to obtain the areas for the vegetation types presented in Table 2.4-4. For instance, estimates of boreal forest area differ by over 8 million km^2. A possible reason for this is that Emanuel et al. (1985) used monthly temperature values to calculate annual biotemperature, whereas Smith et al. (*submitted*) used daily values. Consequently, differences in the percent changes listed in Table 2.4-4 are in part due to differences in how the current vegetation areas were calculated, as well as to how the individual vegetation units were aggregated to form the vegetation units used in the table. The estimated changes in vegetation may also differ because of large differences in the climate scenarios used to drive the vegetation models (see Section 1.4.3).

2.4.4 Research Needs

Predicting the transient response of global vegetation to climate change is essential for estimating biospheric feedbacks and regional sensitivity to climate change, and for evaluating the effectiveness of various mitigation strategies (e.g., reforestation). Current global vegetation models cannot be used to estimate transient vegetation dynamics. Moreover, these models are based on correlations between climate and vegetation, correlations that may not persist under altered climate conditions. Finally, the models do not incorporate soils or the potential effects of CO_2 fertilization on vegetation.

There is much work to be done in producing a dynamic and realistic global vegetation model. The following areas of research need attention in order to develop such a model:

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1)   Development of a plant life-form classification system that can form the basis of a global vegetation model. Life-forms grouped together should have common autoecological characters, such as physiognomy, seed dispersal, and response to macroclimate and soils.

2)   Determination of the ecological mechanisms through which climate controls the distributions of these life-forms.

3)   Incorporation of disturbance and migration into global vegetation models.

4)   Production of global vegetation maps based on remotely sensed data to calibrate and validate vegetation models.

5)   Generation of digitized databases of soil texture and nutrient availability at a resolution appropriate for global modeling.

6)   Calculation of the effects of CO_2 enrichment on ecosystem water-use efficiency.

2.5   Impacts of Climate Change on Biological Diversity

Loss of biological diversity (biodiversity) is becoming one of the most critical environmental issues of the 1990s. Estimates of the annual global rate of species extinction range from 1,000 to 10,000 times the rate before human intervention (Wilson 1988). The basic issue driving concerns about biodiversity is the accelerating and irreplaceable loss of genes, species, populations, and ecosystems. Associated with this loss are the loss of products presently or potentially obtained from nature, the possible disruption of essential ecological processes and"services, and the forfeit of options for biological and cultural adaptation to an uncertain future.

Forested ecosystems account for much of the world's biological diversity. Indeed, the greatest concentration of species diversity in the world is in tropical rain forests. These forests account for only 7% of the earth's land cover, yet they contain at least 50% of all species (Reid and Miller 1989). Current estimates indicate that 1% of this biome is being deforested each year and that another 1% is being significantly degraded (Myers 1988). Thus, much of the current concern about loss of biodiversity has centered on tropical forests. However, maintenance of biodiversity is also very important in temperate areas in which human activities have greatly altered the terrestrial landscape. Temperate forest zones

have been more uniformly and extensively altered by human activities than any other region of the world. Most remaining areas of temperate forests are fragmented and highly modified.

In forested ecosystems, climate change is predicted to cause an intensified loss of biodiversity (Henderson et al. 1989). Projected effects of climate change on forested ecosystems include reductions in species diversity in low-elevation forests as well as elevational and latitudinal shifts in species ranges (Leverenz and Lev 1987). Species are most likely to be stressed at the edge of their ranges. Plants and animal species with low vagility, or that are prevented from migrating by a lack of habitat corridors, may become regionally extinct. Habitat modification and climate change are certain to interact to produce other synergistic effects that will be difficult to predict or mitigate.

Any impact to vegetation from global climate change will be extended to animals through food chains and alteration of habitat structure. Historically, animals have responded to climate changes by following the shifting vegetation assemblages. Gradual change in species composition is a natural response to climate change. However, the projected high rate of climate change over the next few decades is of concern because species with limited dispersal capacities (i.e., with slow rates of migration) may not be able to track shifting climate zones to stay within their limits of physiological tolerance (Peters and Darling 1985). Migrating species will have to contend not only with natural geographic barriers to dispersal, but also with a landscape altered by humans and with barriers such as roads, cities, and agricultural lands.

We have examined existing species richness maps for various taxa (amphibians, reptiles, trees, birds, and mammals, see Figure 2.5-1) to determine current patterns of biodiversity. By overlaying the different taxa maps, areas of high biodiversity can be identified. For example, the southeastern portion of the United States is characterized by large numbers of amphibian, tree, and reptile species, as well as relatively high levels of bird species diversity. Thus, this area is of significant interest for maintenance of biodiversity and further research in understanding species and ecosystem sensitivity to climate change. Preliminary analyses overlaying the density maps on the vegetative change maps (e.g., Figure 2.4-3) generated using the Holdridge system and GCM scenarios, indicate that much of the southern United States could change vegetative cover under double-CO_2 scenarios. Vegetative change will affect animal habitat. Consequently, the southern United States is at high risk of losing species under all GCM scenarios.

AMPHIBIAN SPECIES DENSITY

REPTILE SPECIES DENSITY

TREE SPECIES DENSITY
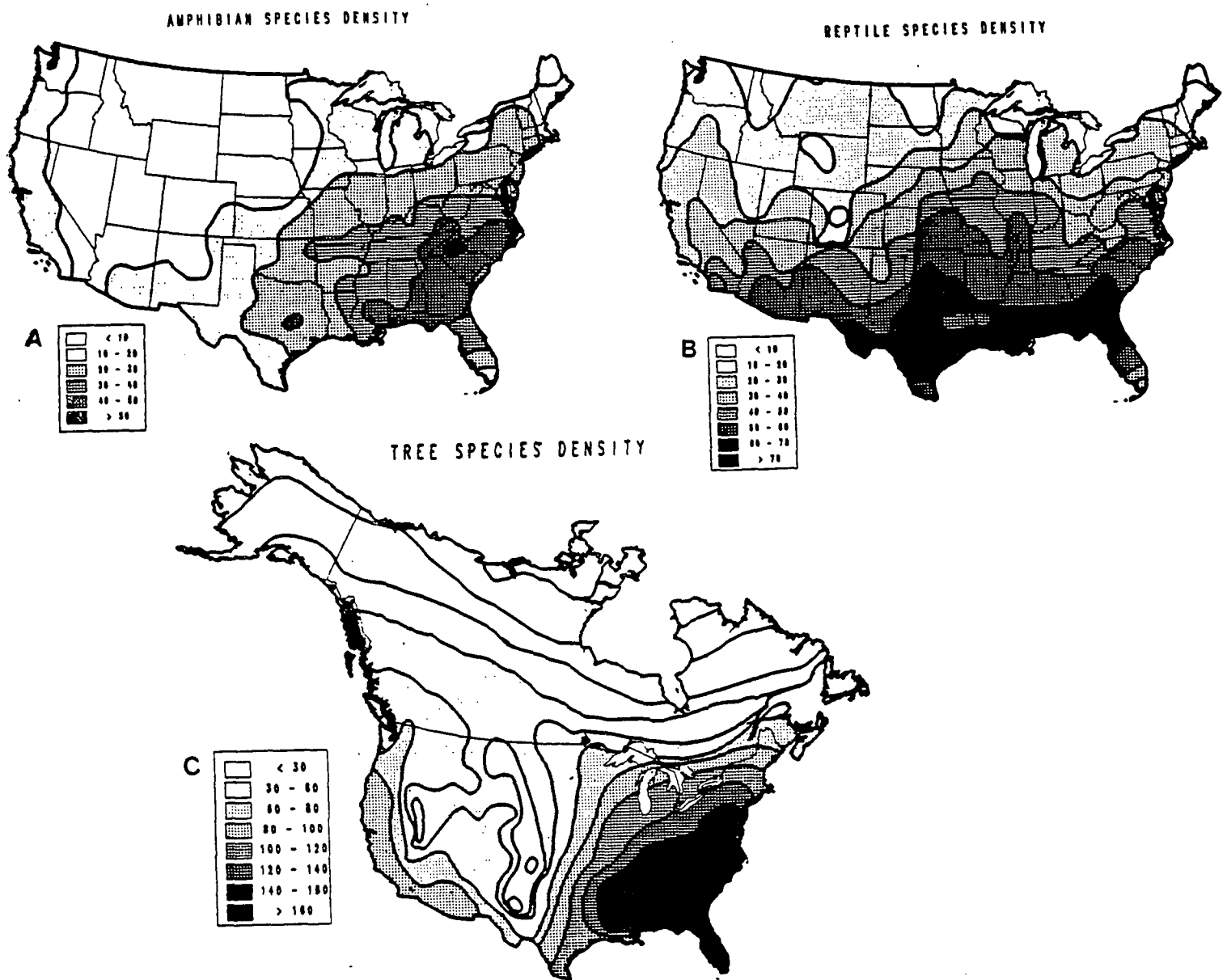
Figure 2.5-1. Density/richness maps illustrating one level of biodiversity for a) amphibians (Kiester 1971), b) reptiles (ibid.), and c) trees (Currie and Paquin 1987) in North America and/or the contiguous 48 United States. Units refer to the number of different species found in that area.

BIRD SPECIES DENSITY

D

	< 40
	40 - 80
	80 - 120
	120 - 160
	160 - 200
	200 - 240
	240 - 280
	280 - 320
	320 - 360
	> 360

MAMMALS SPECIES DENSITY

E

	< 40
	40 - 60
	60 - 80
	80 - 100
	100 - 120
	> 120
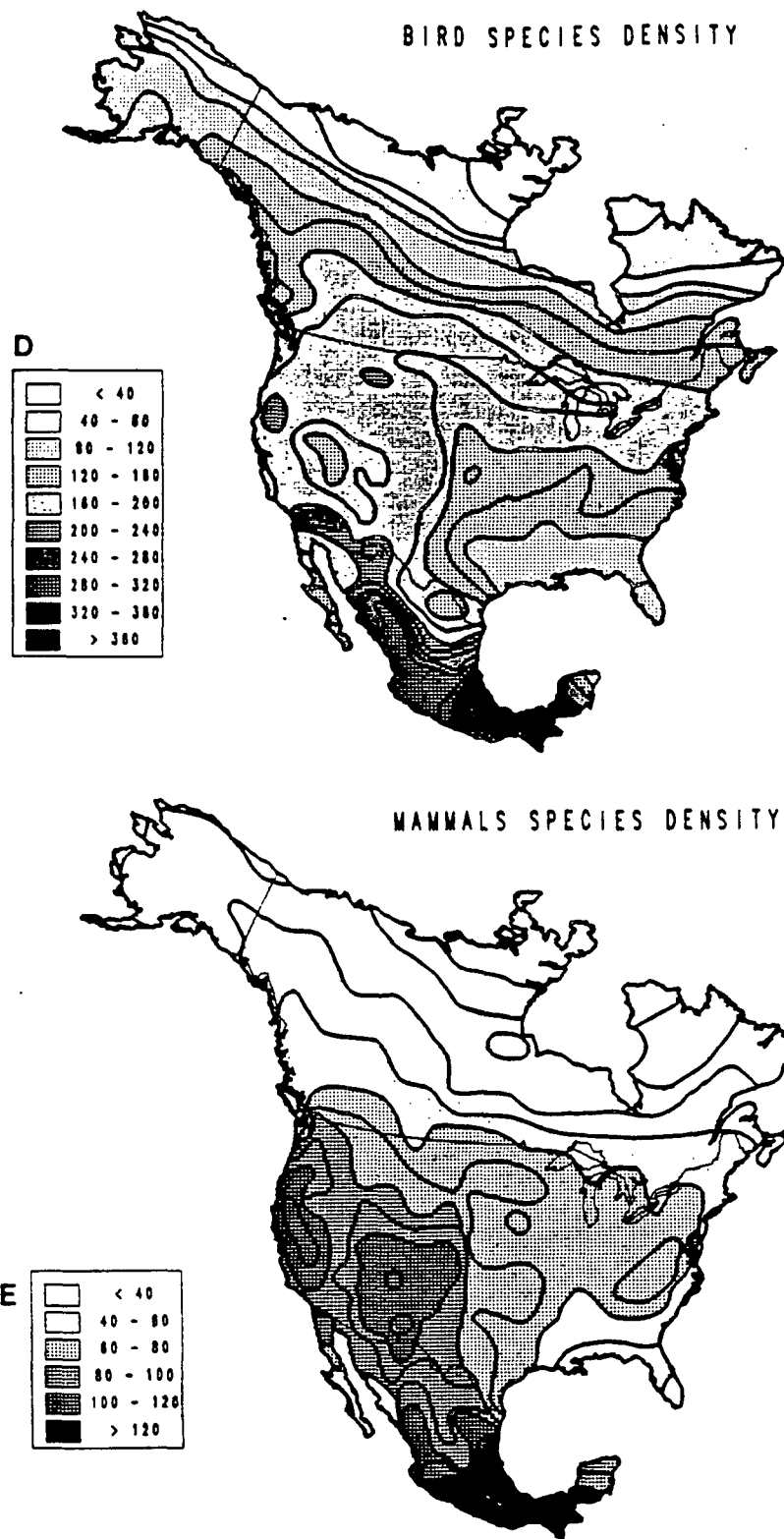
Figure 2.5-1 (Cont'd). Density/richness maps illustrating one level of biodiversity for d) birds (Cook 1969), and e) mammals (Simpson 1964) in North America and/or the contiguous 48 United States. Units refer to the number of different species found in that area.

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Global climate change could have significant consequences for biodiversity. Anticipated effects vary among regions and ecosystem types; thus, it will be necessary to identify those areas where changes would be most catastrophic for biodiversity. Further research is needed on how biodiversity will be affected through projected changes in major vegetation zones. Specific needs are to:

1)   Determine climate and land use controls of biodiversity.

2)   Identify high-diversity, high-risk ecosystems.

3)   Identify vulnerable species and guilds at a regional and continental scale. Analyze specific species at risk, their life history characteristics, and the availability of suitable habitat and or corridors for migration and dispersal.

3 FEEDBACKS: TERRESTRIAL CARBON STORAGE

Changes in global vegetation of the magnitude described in Section 2.4 will have a significant impact on terrestrial carbon storage and will thus act as a positive or negative feedback to climate change. In Section 3.1, the amount of above- and belowground carbon associated with vegetation in a double-CO_2 atmosphere is estimated. In Section 3.2, the analysis is expanded to estimate the dynamics in terrestrial carbon associated with vegetation change from the present to a double-CO_2 atmosphere.

3.1   Effects of Climate Change on Carbon Storage in Terrestrial Ecosystems: Equilibrium Analyses at the Global Level

The objective of this section is to investigate the potential for a net flux of carbon between the terrestrial biosphere and the atmosphere due to climate change. This is an equilibrium analysis (i.e., the assumption is made that climate and vegetation are always in equilibrium), and a bookkeeping approach is used in which: 1) vegetation types are distributed across the land surface based on the current climate and double-CO_2 climate scenarios using an existing vegetation-climate correlation system (Holdridge 1947); 2) the vegetation types are assigned representative above- and belowground carbon pool values; 3) terrestrial carbon storage is summed by climate scenario; and 4) the differences between current storage and future storage are determined.

3.1.1 Methods

3.1.1.1 Vegetation data

The double-CO_2 atmosphere simulations of global vegetation generated by Leemans (1990) and Smith et al. (submitted) and summarized in Section 2.4 were used in this analysis. Holdridge life zones were aggregated into biomes following the scheme shown in Table 3.1-1.

Table 3.1-1.   Aggregation Scheme for Combining Holdridge Life Zones into Biomes (Cramer and Leemans *in press*)

	Biome	Holdridge Zone
		Ice
		Polar Desert
1	Tundra	Subpolar Dry Tundra
		Subpolar Moist Tundra
		Subpolar Wet Tundra
		Subpolar Rain Tundra
2	Cold Parklands	Boreal Desert
3	Forest Tundra	Boreal Dry Scrub
4	Boreal Forest	Boreal Moist Forest
		Boreal Wet Forest
		Boreal Rain Forest
5	Cool Desert	Cool Temperate Desert
		Cool Temperate Desert Scrub
6	Steppe	Cool Temperate Steppe
7	Temperate Forest	Cool Temperate Moist Forest
		Cool Temperate Wet Forest
		Cool Temperate Rain Forest
8	Hot Desert	Warm Temperate Desert
		Warm Temperate Desert Scrub
		Subtropical Desert
		Subtropical Desert Scrub
		Tropical Desert
		Tropical Desert Scrub
9	Chaparral	Warm Temperate Thorn Steppe
10	Warm Temperate Forest	Warm Temperate Dry Forest
		Warm Temperate Moist Forest
		Warm Temperate Wet Forest
		Warm Temperate Rain Forest
11	Tropical Semi-Arid	Subtropical Thorn Woodland
		Tropical Thorn Woodland
		Tropical Very Dry Forest
12	Tropical Dry Forest	Subtropical Dry Forest
		Tropical Dry Forest
13	Tropical Seasonal Forest	Subtropical Moist Forest
		Tropical Moist Forest
14	Tropical Rain Forest	Subtropical Wet Forest
		Subtropical Rain Forest
		Tropical Wet Forest
		Tropical Rain Forest

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3.1.1.2 Carbon pools

Aboveground carbon ranges from 25 kg/[2] in dense forests to less than 0.5 kg/m^2 in the arctic (Olson et al. 1983). The summary of Olson et al. (1983) was used as a basis for assigning aboveground carbon pool values to the aggregated Holdridge vegetation types (Table 3.1-2). Belowground carbon pools were assigned to the Holdridge vegetation types (Table 3.1-2) based on a study by Post et al. (1982) in which data from 2696 global sites were used to construct isolines for belowground carbon storage within the Holdridge climate diagram (Figure 3.1-1). Based on the current climate, this analysis estimated totals for aboveground carbon (852 Gt) and belowground carbon (1456 Gt) that are consistent with other studies (Schlesinger 1977, Woodwell et al. 1978, Oades 1988).

Certainly there is large spatial heterogeneity in these pools within each vegetation type, but evaluation of that heterogeneity will require detailed survey information that is not currently available. Mean values were used in this analysis as a first approximation to account for the spatial heterogeneity.

The absolute value of the representative carbon pools is also in question. Recent analysis of boreal forest ecosystems (Botkin and Simpson 1990) suggests that previous estimates of aboveground carbon in these and other ecosystems have been uniformly high. Additional studies, probably coordinated with remote sensing, are needed to evaluate this question. In the present analysis, the carbon pools associated with each vegetation type were held constant, and a difference between current and future storage was calculated. Thus, the approach is not particularly sensitive to consistent overestimation of above- or belowground carbon across all vegetation types.

Table 3.1-2. Above- and Belowground Carbon Pools for World Biomes

	Biome	Carbon Density[1] (kg/m³) Above-ground	Below-ground
1	Tundra	0.5	22.0
2	Cold Parklands	0.8	10.0
3	Forest Tundra	6.0	11.0
4	Boreal Forest	11.0	15.0
5	Cool Desert	0.6	9.0
6	Steppe	1.5	13.0
7	Temperate Forest	11.0	18.0
8	Hot Desert	0.4	1.0
9	Chaparral	4.0	8.0
10	Warm Temperate Forest	10.0	10.0
11	Tropical Semi-Arid	5.0	4.0
12	Tropical Dry Forest	7.0	7.0
13	Tropical Seasonal Forest	10.0	11.0
14	Tropical Rain Forest	15.0	19.0

1Aboveground data after Olson et al. 1983; belowground data after Post et al. 1982
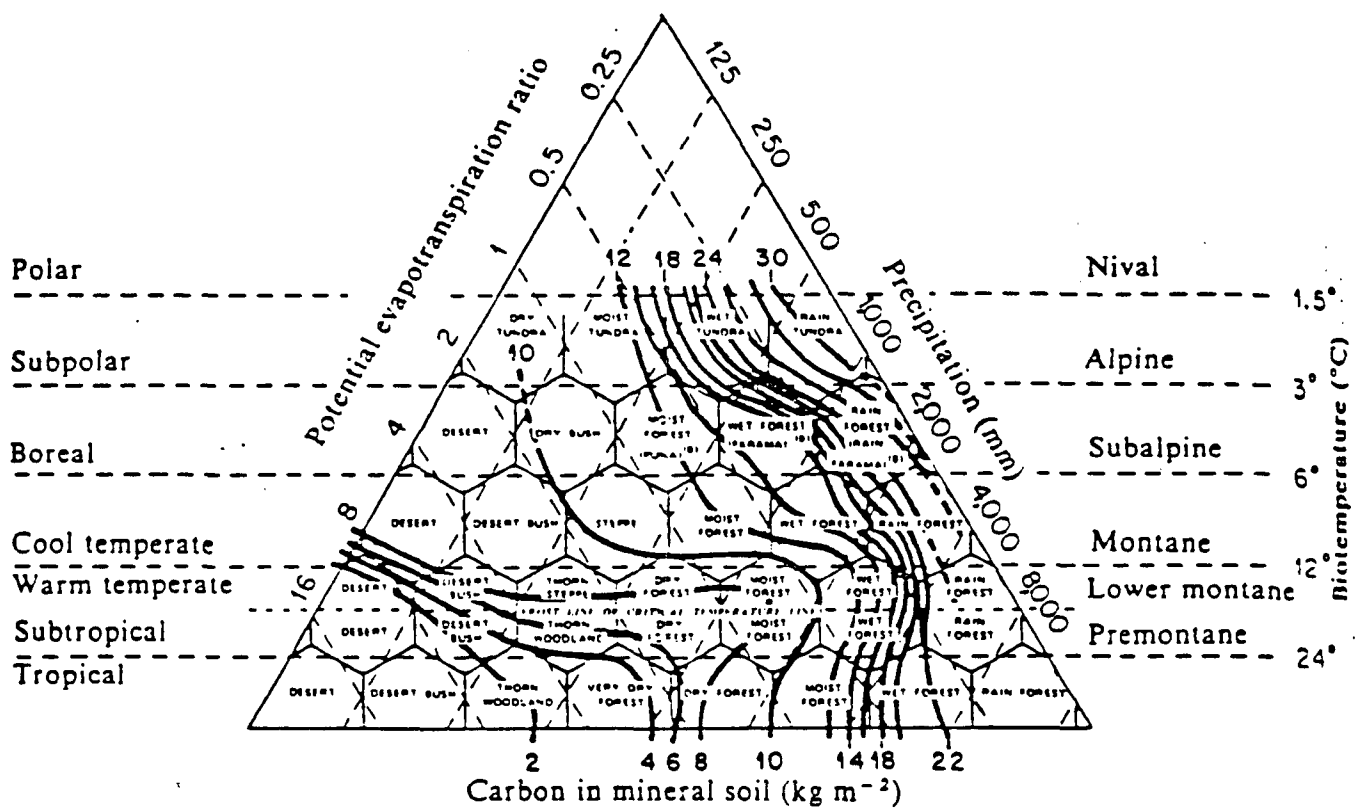
Figure 3.1-1. Relationship of belowground carbon pools to Holdridge life zones (Post et al. 1982).

3.1.2 Results and Discussion

Differences in the areal extent of the biomes, as predicted by four GCMs, are listed in Table 3.1-3. Results for the four GCMs show some basic similarities. At middle to high latitudes, tundra and boreal forests contract, and temperate forest (mostly coniferous) expands. In the tropics, both the semi-arid woodland and the tropical rain forest have large increases in areal extent, mostly at the expense of tropical seasonal forests.

Table 3.1-3. Changes in Areal Extent of Different Vegetation Types as Predicted under Four GCM
Scenarios (Smith et al. *submitted*)

Biome		Area (10^6 km^2)	GFDL	Difference in Biome Area (10^6 km^2) GISS	OSU	UKMO
1	Tundra	9.30	-6.11	-5.05	-4.56	-6.43
2	Cold Parklands	2.79	0.03	-0.41	-0.10	-1.09
3	Forest Tundra	8.90	-5.02	-3.03	-2.90	-5.50
4	Boreal Forest	15.03	-5.45	-1.54	-0.89	-4.85
5	Cool Desert	4.01	-0.97	-1.67	-0.82	-1.93
6	Steppe	7.39	4.20	-0.46	1.30	-0.21
7	Temperate Forest	9.94	1.92	3.49	1.63	3.04
8	Hot Desert	20.85	-0.20	-3.22	-1.42	-0.92
9	Chaparral	5.58	1.83	-0.13	-0.69	2.99
10	Warm Temperate Forest	3.17	-1.22	-1.25	-0.72	-0.29
11	Tropical Semi-Arid	9.56	4.43	7.18	2.58	7.07
12	Tropical Dry Forest	14.86	4.71	4.49	-0.00	11.19
13	Tropical Seasonal Forest	15.13	-5.11	-7.24	-4.98	-7.48
14	Tropical Rain Forest	8.46	6.95	8.85	11.57	4.40
	Total	134.97				

Analysis of changes in carbon storage reveals that all climate scenarios predict an uptake of carbon from the atmosphere ranging from 37 to 116 Gt for the aboveground component of the biosphere (Figure 3.1-2). There are great discrepancies between the model runs for the change in belowground carbon storage. The UKMO model predicts a flux to the atmosphere of 126 Gt, whereas the OSU model predicts a belowground accumulation of 37 Gt. The large fluxes to the atmosphere appear to be associated with loss of carbon from reduction in tundra and boreal forest areas, both of which have relatively high levels of belowground carbon.
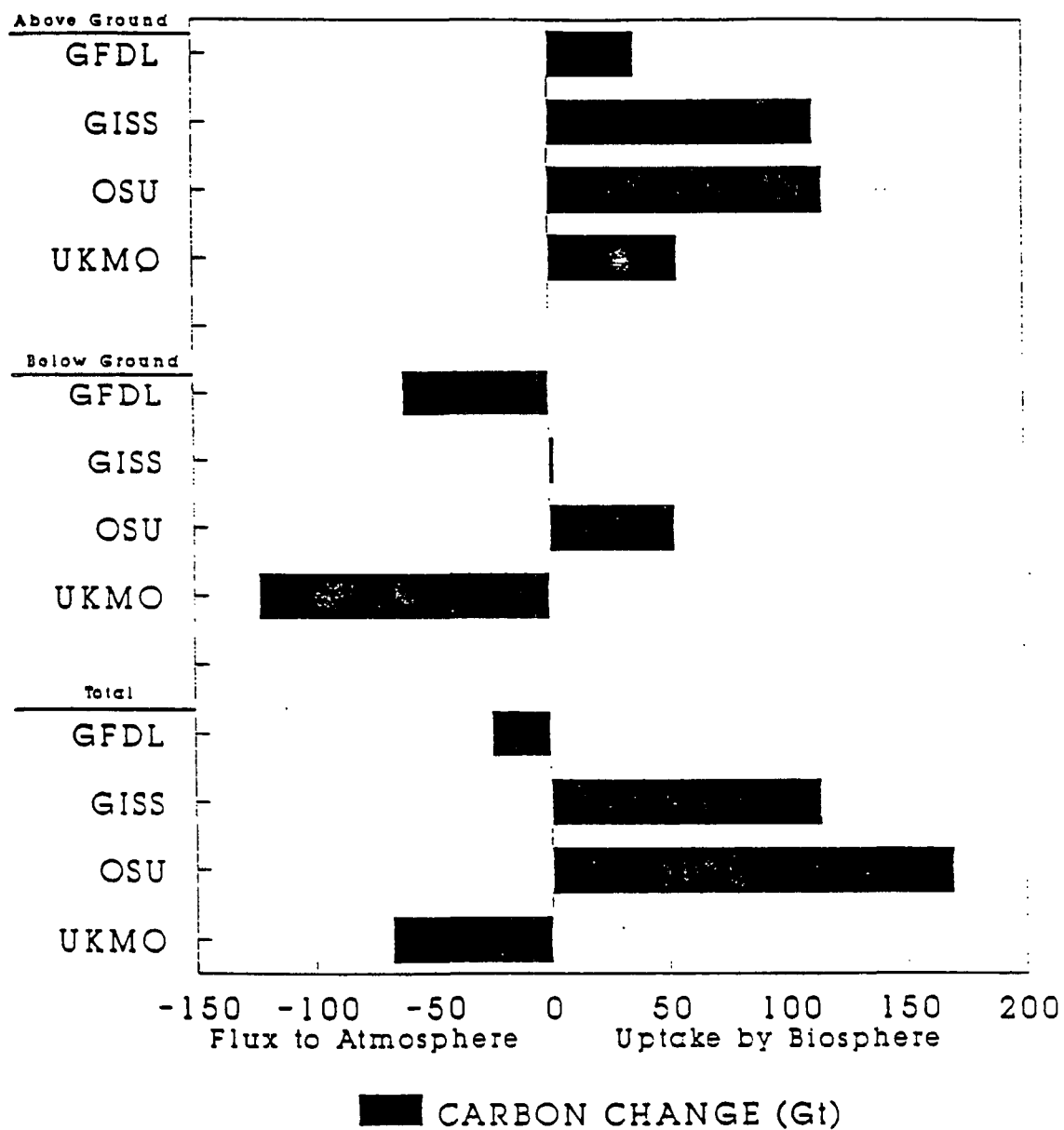
Figure 3.1-2. Potential changes in terrestrial carbon storage based on redistribution of vegetation types.   Values are differences   between   stored   carbon   under   the   current   climate and under double-CO $_2$ climates as predicted by four CGMs.

The net change of above- and belowground carbon ranged from a 169 Gt uptake predicted by the OSU model to a 68 Gt release predicted by the UKMO model. A key question appears to be how great the gains will be in tropical rain forest. Because both above- and belowground components have high carbon storage in these forests, the changes from tropical dry forest to tropical wet forest tend to drive the global trends. In terms of climate, the question is whether precipitation will substantially increase in tropical and subtropical latitudes.

A number of other investigators have estimated potential changes in carbon storage based on the climate-vegetation correlation systems and other GCM double-CO_2 climate scenarios. For aboveground carbon, Sedjo and Solomon (1989) predicted a net flux of 13.9 Gt to the atmosphere. Much of that change in aboveground carbon was accounted for by loss of boreal forest and increases in savanna. Lashof (1987, 1989), evaluating potential above- and belowground changes, reported a range from a 64 Gt uptake from the atmosphere to a 26 Gt release, again depending on the GCM used. A modified Holdridge classification system (Prentice 1990), which better represented the current vegetation, suggested a much greater potential flux of carbon (270 Gt) to the surface pools of above- and belowground carbon (Prentice and Fung in press). As in our analyses, the uptake was related primarily to expansion of the tropical rain forest biome which has relatively high levels of above- and belowground carbon.

To evaluate the magnitude of feedbacks associated with these carbon fluxes, it is necessary to know: 1) how much of the carbon would be retained in the atmosphere (in the case of a positive feedback); 2) what the radiative forcing of the CO_2 added or removed from the atmosphere would be; and 3) what the sensitivity of the climate system is to that forcing. Likewise, for a negative feedback, the magnitude can most readily be evaluated via the impact on atmospheric CO_2 concentration.

The proportion of carbon released to the atmosphere due to fossil fuel combustion and deforestation that has accumulated in the atmosphere has been approximated at 40% (IPCC 1990). The remainder has been taken up by the ocean, in part due to photosynthetic uptake of CO_2 by plankton, and by the terrestrial biosphere via a net imbalance between CO_2 assimilation during photosynthesis and CO_2 loss via plant, animal, and microbial respiration. The atmospheric retention factor is difficult to determine because of uncertainties about many terms in the global carbon cycle (Keeling et al. 1989). It is also likely to change over the coming decades in response to factors such as CO_2 fertilization of plants and warming of the ocean.

Assuming a retention factor of 40%, the 68 Gt release of carbon in the case of the maximum positive feedback discussed earlier would result in a 27 Gt increase in the atmospheric pool. Given a net change in the atmospheric carbon pool, a conversion to a change in atmospheric CO_2 concentration can be made using an approximation of 2 Gt carbon to 1 ppm CO_2. Thus, the increase would be about 13 ppm CO_2. In the case of a negative feedback, Gt can be converted directly into ppm CO_2 extracted from the atmosphere by dividing by two.

The estimation of a climate forcing associated with a change in atmospheric CO_2, independent of feedbacks in the climate system, is relatively straightforward (Hansen et al. 1988) and the GCMs are in general agreement (Cess et al. 1989). Following the approach of Hansen, the climate forcing of 13 ppm added to a reference CO_2 concentration of about 450 ppm for a double-CO_2 climate (the rest of the warming being provided by other trace gases), is about +0.05°C. The effect of subtracting 84 ppm (169Gt/2) would be about -0.28°C. These values compare with the double-CO_2 climate forcing without feedbacks of +1.25°C. The GCMs are in much less agreement in accounting for various feedbacks in the climate system given an initial forcing (Hansen et al. 1984). The total climate forcing for the given potential changes in CO_2 is thus much less certain. However, the total effects would probably scale to the magnitude of the original forcing, so a maximum negative feedback of perhaps 20% of the original forcing is predicted from this analysis due to changing terrestrial carbon pools.

3.1.2.1 Modifiers and uncertainties

The most troublesome assumption using the equilibrium approach described here is that the climate/vegetation correlation will remain constant. Physiological responses of plants to CO_2 suggests that water-use efficiency increases with ambient CO_2 concentration. If this effect is large, aboveground carbon associated with a particular water regime might be expected to increase, and thus the magnitude of the predicted feedbacks associated with carbon·pool changes would be different.

A second concern is that the analysis assumes that climate and vegetation are now, and will remain, in equilibrium. In fact, the predicted rates of climate change (>0.1°C per decade) are an order of magnitude faster than what natural systems experienced during the glacial-interglacial cycles of the Pleistocene period. Analyses of tree seed dispersal distances and pollen records indicate that the rate of climate change may exceed rates of vegetation redistribution (Davis 1981). The predicted discrepancy between these rates may have significant implications for changes in aboveground carbon pools. Large transient carbon fluxes could occur if there is a rapid burnoff of carbon as the vegetation

drifts out of equilibrium with climate, and vegetation recovery is slow because of both limited migration rates for appropriate species and slow regrowth.

There will also be lags in the equilibrium between belowground carbon pools and climate. Where carbon gains are expected, as with the transition from tropical seasonal to tropical rain forest, there are few data to predict how rapidly the accumulation would occur. Factors such as soil mineralogy and texture may have strong local influences (Oades 1988). Land use considerations will likewise influence carbon storage because of the tendency for cultivation to decrease stored carbon.

Where equilibrium analyses suggest a reduction in belowground carbon, an important consideration will be the fractionation of the soil organic matter. Microbial respiration increases with temperature, assuming optimal moisture, but belowground carbon is not all readily oxidizable. A large proportion of grassland soil carbon pools has been classified as recalcitrant to decomposition, with a turnover time of up to 1000 years (Parton et al. 1988). Forest soils are also characterized by a large recalcitrant fraction, and lags in the reduction of soil organic matter due to warming may be on the order of hundreds of years. Continued research on the mechanisms and modeling of soil organic matter turnover is needed.

These analyses also ignore the large influence that humans will have on rates of vegetation change. Currently anthropogenic factors use or co-opt approximately 40% of the earth's potential net primary production, and over large areas the productive capacity of the land is being reduced (Vitousek et al. 1986). Land used for human purposes will probably not be readily converted to the high carbon-storage vegetation types predicted in this analysis. However, humanity may be able to promote changes that would favor carbon sequestration. Management options are available to reduce carbon fluxes to the atmosphere and maximize carbon sinks associated with the terrestrial biosphere. Their implementation will require an understanding of current climate-vegetation-soil relationships and of locations where the climate will favor specific vegetation types in decades to come.

3.1.3 Conclusions

These equilibrium analyses suggest that the changes in terrestrial carbon pools induced by climate warming could provide a moderate negative feedback to that warming. That is, as global warming increases, carbon storage will increase and the overall increase in atmospheric CO_2 concentration will be moderated. The greater the increase in precipitation for the low latitudes, and thus in tropical wet forest area, the stronger that feedback will be. These analyses do not consider: 1) potential short-term fluxes of carbon due to changing disturbance regimes; 2) the relatively slow response of belowground carbon

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pools to climate change; or 3) potential enhancements or reductions of carbon storage due to management practices.

3.2 Biosphere Feedback During Climate Change

The previous section discussed the impact on the terrestrial carbon pool of a redistribution of global vegetation. That analysis focused exclusively on comparing the carbon stored in the terrestrial biosphere before and after a climate change brought about by a doubling of atmospheric CO_2 assuming vegetation was in equilibrium with climate after the climate change. This section expands on that analysis by estimating the transient (time-dependent) effects of changing vegetation on the aboveground terrestrial carbon pool and carbon fluxes to the atmosphere.

Consider first the vegetation dynamics induced by a double-CO_2 atmosphere climate change. According to Leemans (1990) and Smith et al. (submitted) (see Section 2.4 for a summary of Leemans' results), there will be a poleward shift in the extratropical forests and expansion of the tropical forests using the Holdridge life zone model. The total area of extratropical forests is not expected to change a great deal under a double-CO_2 climate, with estimates ranging from 83% (GFDL) to 102% (GISS) of the current area. However, 46% (OSU) to 88% (UKMO) of the southern extent of the extratropical forests would be displaced toward the poles. Estimates of tropical forest expansion are similar, ranging from 116% (GISS) to 121% (UKMO) of their current area. The Box biosphere model (Box 1981) produces similar results in the extratropics, but it predicts a decline in tropical forests due to an upper thermal limit (Smith personal communication).

During the simulated vegetation change from current to double-CO_2 climate conditions, three processes will dominate the impact of these changes on global carbon dynamics:

1)   As forests shift poleward, their equatorward extents should go through a decline with concurrent carbon release (see following discussion). This is a critical assumption that requires further research to confirm it (Solomon 1986, Smith and Tirpak 1989, Neilson et al. 1989, Bonan et al. 1990, Overpeck et al. 1990).

2)   New vegetation will advance and regrow in recently opened landscapes (defined here as the "change" zone), and the new vegetation will begin sequestering carbon.

3)   As the tropical forests expand (according to Smith et al. submitted), they will sequester more carbon. This assumption also requires further research.

The balance of these three processes, one releasing and two sequestering carbon, will determine the net transient source or sink impact of the biosphere on the atmospheric carbon concentration. In a study conducted at ERL-C, a simple model of these three rate processes was developed, and a preliminary sensitivity analysis of the key parameters was performed with respect to atmospheric loading of CO_2. This section presents the results of this analysis for forest systems (as described in Section 1.4.2, forest systems contain the bulk of the carbon in the terrestrial biosphere and, for simplicity, they were the only biomes considered in this analysis). The analysis was restricted to aboveground organic matter dynamics. Belowground carbon pools are also expected to change in the same direction as the aboveground change, but the potential decline rate would be slower than that in the aboveground component. The conclusions, based solely on aboveground carbon, should thus be conservative with regard to transient carbon loading of the atmosphere.

The most critical process in the analysis is the removal of the extant forest from the zone of change. If this were to occur through competitive displacement, the release of carbon would be slow or insignificant. However, as forests are stressed climatically, which is probable under the range of current GCM climate projections (Neilson et al. 1989), their decline stage would likely be mediated by catastrophic disturbance, particularly by fire (Bonan et al. 1990, Neilson et al. 1989, Overpeck et al. 1990, Winjum and Neilson 1989). Arguments exist for both processes, i.e., competitive displacement and catastrophic decline.

The boundary between the boreal and temperate forests is apparently controlled by cold temperature, the -40°C isotherm (Burke et al. 1976). If this climate boundary shifts north, one might anticipate a simple competitive replacement of boreal by temperate species with no increase in disturbance or significant change in carbon pools. However, water availability must also be considered. Within their boundaries, most of the world's biomes may be transpiring most of their available soil water resources during each growing season (Woodward 1987, Neilson et al. 1989).

More water could become available through altered potential evapotranspiration, rainfall, or water-use efficiency (WUE) of the vegetation. In theory, if more water were available, more leaf area would be generated, thus water would be transpired. If a landscape contains too much leaf area, water is transpired too rapidly and is depleted before the end of the growing season, causing drought-induced vegetation decline that reduces leaf area. As a result of these feedback processes, regional biomass

levels should be in rough equilibrium with the regional water balance. A rapid change in that water balance, through increased potential evapotranspiration (PET), decreased rainfall (P), or increased deficit (PET - P), should produce drought-induced vegetation decline.

Thus, global increases in temperature may allow some boundaries to shift. However, the concomitant rise in PET could deplete soil water reserves, causing widespread drought-induced decline (Bonan et al. 1990, Neilson et al. 1989, Solomon 1986, Smith and Tirpak 1989). Marks (submitted) calculated PET under current and double-CO_2 conditions for the continental United States. Large increases in PET are projected to occur over much of the United States. Anticipated increases in rainfall in northern latitudes would not likely be sufficient to balance the increased PET (Bonan et al. 1990, Grotch 1988). Catastrophic fires, induced by the increasing frequency of extreme events such as drought and high wind (Bonan et al. 1990, Neilson et al. 1989, Overpeck et al. 1990) are assumed here to be the dominant mechanism removing forests from the change zone. Drought stress could also increase the intensity of pest infestation, which also usually results in catastrophic fire. These generalizations may not hold in the far north where some biomes may be limited more by energy than by water (Woodward 1987).

3.2.1 The Model

The rate of CO_2 loading to the atmosphere during the decline period will be determined by: 1) the amount of direct combustion; 2) the efficiency of combustion; 3) the amount of residual, dead organic matter; 4) the rate of decay of that organic matter; and 5) the amount of carbon lost to surface waters. The simplest assumptions are that the annual rate of area burned will track the rate of climate change (likely after some lag period), and that any carbon shunted to surface waters will be rapidly released as CO_2. If a doubling of CO_2 is expected to occur in 50 years, then the entire change zone would burn off in a 50-year period. This appears to be an extreme assumption, invoking a massive and continuous amount of wildfire affecting much of the world's forested area. The alternative, if the assumption of extreme drought is accepted, is that the rate of forest incineration will lag behind the rate of climate change. Ecosystems would then be subjected to ever-increasing levels of drought, producing considerable amounts of dead biomass. It is thus an equally extreme assumption to presume that vast amounts of standing dead biomass would not eventually burn off. The prospect of climate change forces upon us the examination of almost unimaginable ecological scenarios. The intent of this exercise is to attempt to bound the extent of ecological change and the resulting biospheric feedback to the atmosphere. Through a focused sensitivity analysis of the important model parameters, including the rate of decline, we hope to help set priorities for future research.

Carbon loss from catastrophic forest dieback was modeled as a combination of two processes: the fraction directly incinerated followed by exponential decay of the remaining large fragments. Imagine that the current climate over a biome is a veil. As the climate changes, the veil shifts slowly toward the pole, revealing a constant fraction of the eventual change zone each year. If N_R is defined as the total aboveground organic matter in the change zone that will be incinerated over n years, then the fractional organic matter available for combustion each year is as follows:

$$N_p = \frac{N_R}{n} \qquad (3.2-1)$$

where N_p is the aboveground organic matter per land parcel that will eventually be lost. A new parcel becomes susceptible each year. The CO_2 emissions from a single parcel over time are calculated as follows:

$$E_i(t) = N_p - N_p(1-f) e^{-kt} \qquad (3.2-2)$$

where E_i is the accumulated amount of carbon emitted from parcel i at time t from the combination of: 1) direct incineration of a fraction, f, of aboveground organic matter when the parcel became susceptible; and 2) subsequent decomposition at rate k/yr of the remaining aboveground organic matter on that parcel. The remaining organic matter is assumed to be large woody debris with 100% mortality of aboveground vegetation.

The temporal release of CO_2 from each parcel will be identical to all other parcels. Parcel emissions are simply initiated sequentially, one each year. Thus, one only need calculate the time-dependent emissions from one parcel. The total regional emissions at time t can be calculated from the single parcel by summing emissions from time 1 to time t, for t less than or equal to n, and from $(t-n)+1$ to t, for t greater than n. The accumulated regional release of CO_2 over all parcels up to time t, $E_R(t)$, is thus modeled as follows:

$$E_R(t) = \begin{cases} \displaystyle\sum_{j=1}^{t} E_i(j) \, , & \text{for } t \leq n \\ \displaystyle\sum_{j=(t-n)+1}^{t} E_i(j) \, , & \text{for } t > n \end{cases} \qquad (3.2-3)$$

Equations 3.2-2 and 3.2-3 form a hierarchical set with Equation 3.2-2 simulating the carbon release from

a parcel and 3.2-3 the accumulated release over the region. The parcel-level process rates and the regional rate of new parcels becoming susceptible are thus combined for the regional emissions estimate.

Once burned, a parcel becomes available for regrowth and the gradual accumulation of more organic matter. Net Ecosystem Productivity (NEP) is the total accumulation of organic matter per year accounting for carbon losses due to both autotrophic and heterotrophic respiration (Peet 1981, Sprugel 1985, Waring and Schlesinger 1985, Shugart 1984, Whittaker 1975). In general, NEP is low after disturbance, gradually increases to a maximum during mid-succession, and approaches zero as the ecosystem approaches a carrying capacity in late succession. The sigmoid curve produced by the logistic equation was used to model this process:

$$\frac{dN_i}{dt} = rN_i \frac{(K_i - N_i)}{K_i} \qquad (3.2-4)$$

where dN_i/dt is the aboveground NEP on parcel i, K_i is the carrying capacity of carbon in units of kg/m^2 on parcel i, and N_i is the organic carbon accumulated at time t on parcel i. In demography, r is the intrinsic rate of increase (birthrate - deathrate). In our use r does not carry an exact definition, but would represent an intrinsic production capacity (Emanuel et al. 1984, Harvey 1989). In the early stages of succession, actual aboveground NEP is much lower than r, due to a lack of vegetation capable of fixing carbon, i.e., modulation by N_i (Peet 1981, Waring and Schlesinger 1985). In the later stages of succession, aboveground NEP is low because decomposition nearly balances carbon fixation, i.e., modulation by K.

Traditionally, carbon fixation and decomposition processes would be modeled explicitly to calculate dN_i/dt (Emanuel et al. 1984, Harvey 1989). However, observations of aboveground organic matter changes are direct observations of *net carbon gain* (NEP, aboveground), rather than observations of r. Therefore, observed literature values of aboveground NEP were substituted in Equation 3.2-4 for dN_i/dt, and were assumed to be the maximum values. The term r is then calculated using Equation 3.2-4 from the maximum observed dN_i/dt (NEP), where $N_i = K_i/2$ at maximum NEP (Ricklefs 1973)

and is substituted into Equation 3.2-5 below.[3] Again, this can be viewed from the theory of hierarchies (Allen and Starr 1982, O'Neill et al. 1986), whereby NEP is an ecosystem property constrained by the external environment and following a simple sigmoid curve (Sprugel 1985). Thus, for our purposes, there is no need to know or simulate directly the production and respiration of carbon, only the net process of organic carbon accumulation. The accumulation of organic carbon over time on parcel i can then be calculated by integrating Equation 3.2-4 as follows:

$$N_i(t) = \frac{K_i}{1+[(K_i-N_{io})/N_{io}]e^{-rt}} . \qquad (3.2-5)$$

Integration of Equation 3.2-4 introduces a new parameter, N_{io}, the initial post-disturbance organic carbon on parcel i. As with regional emissions (Equation 3.2-3), the regional accumulation of organic carbon, N_R, is modeled hierarchically using an initial 'growing window' and then a 'moving window' as an accumulator over a single parcel through time, as follows:

$$N_R(t) = \left| \begin{array}{ll} \sum_{j=1}^{t} N_i(j) , & \text{for } t \le n \\ \sum_{j=(t-n)+1}^{t} N_i(j) , & \text{for } t > n \end{array} \right. \qquad (3.2-6)$$

In summary, parameter estimates must be supplied for dN_i/dt and K and substituted into Equation 3.2-4 which is solved for r. This completes the input parameters for Equation 3.2-5 which is iterated through time (t) for a single parcel. The resulting sigmoid curve is subjected to an 'accumulator window' to estimate the regional time series of carbon accumulation N_R

Tropical expansion was modeled as an increase in the carrying capacity, K, over the area into which the forests expanded according to Equations 3.2-4 through 3.2-6. The current total organic carbon of tropical forests (including moist, dry, and seasonal tropical forests) was parceled by n years. This produced an initial starting organic carbon (N_{io}) per parcel of about 10 kg/m², which was less than

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[3] Observed values of NEP are more likely an average over a bell-shaped trajectory of the true NEP through time. Therefore, actual maximum values for NEP are likely somewhat higher than the average observed values.

moist tropical forests (15 kg/m²), about the same as tropical seasonal forests, and greater than that of dry tropical forests (7 kg/m², Table 3.1-2). The total increase in aboveground organic carbon in tropical forest under a double-CO_2 climate was parceled uniformly over the duration of change and added to the initial organic carbon per parcel, N_{i0}. That is, each year a new parcel of tropical forest became available for additional growth, its carrying capacity was raised, and growth ensued until the new carrying capacity was reached. Since the tropical N_{i0} is rather high, the initial calculated r was also high. Thus, new tropical growth was always begun to the right of the inflection point on the sigmoid curve produced by Equation 3.2-5. Although dN_i/dt was set artificially high for the tropical forests so that the calculated r value would be in a realistic maximum range, it declined rapidly as the new carrying capacity was approached.

Expansion of tropical forests is assumed to occur through competitive displacement or augmented growth of existing tropical forests. The expansion is predicted by the Holdridge model primarily because of large increases in rainfall that are not offset by increased PET. Thus, as discussed earlier, more available water should result in increased biomass and leaf area of the existing ecosystem (Woodward 1987). We infer no catastrophic declines or fires in the tropics. Therefore, Equations 3.2-2 and 3.2-3 for carbon loss only pertain to the extratropical forest dynamics.

Parameter values and initial conditions were determined from the literature. All parameter values were subjected to a sensitivity analysis with regard to the magnitude of the extratropical emission pulse, both with and without tropical expansion.

Emissions of CO_2 from declining forests through drought and fire (Equation 3.2-2) require two parameter estimations. The percentage of organic carbon released through direct incineration, f, was set at 10% (AuClair 1985, Fahnestock and Agee 1983). The decomposition rate, k, was set at 0.05/yr (AuClair 1985, Edmonds 1987).

Both the tropical and extratropical growth rates (NEP) were set somewhat higher than the highest literature values. Recall that these growth rates are used as the maximum that could occur in calculating r. The observed NEP values are usually linear averages of organic carbon gained over some period of time. That is, if a system gained x amount of organic carbon over 100 years, annual NEP would be calculated as $x/100$. Of course, if the true trajectory over 100 years were a sigmoid curve, the early and late succession NEP rates would be lower than average, whereas NEP during mid-succession would be higher than average. Thus, the choice for the maximum values of NEP was set higher than

observed average values. The NEP values were also set high to ensure that our estimates of a CO_2 emission pulse were conservative.

All temperate and boreal forests have been aggregated, and average parameter values for the aggregate have been imposed (Table 3.2-1). Extratropical maximum aboveground NEP was set at 2 t/ha/yr of organic carbon (AuClair 1985, Bormann and Likens 1979, Waring and Schlesinger 1985). Aboveground extratropical forest carbon averaged about 10 kg/m² (Section 3.1), and the area was set at 28.14 million km² (Section 2.4, Table 2.4-2) for a total aboveground carbon storage of about 306 Gt, compared with an estimated 283 Gt (Whittaker 1975, Olson et al. 1983). The initial organic carbon from which regrowth begins was set to 0.4 kg/m², equivalent to two years of maximum NEP. There are very few data with which to estimate initial post-fire organic carbon, but this number appears to agree with current information (AuClair 1985, Johnson and van Cleve *personal communication*). Sensitivity analyses were performed on all key parameters.

Several Holdridge tropical categories were aggregated, including dry, seasonal, and rain forests (see Section 2.4, Table 2.4-2). These different types range from relatively low to quite high standing organic carbon, with an average value of about 10 kg/m². So as not to impose a low initial growth rate, N_0 was set to about 10 kg/m², upon which was grown approximately 1.5 kg/m², depending on the scenario. Maximum tropical NEP was set to 16 t/ha/yr of organic carbon. Our preferred value for tropical NEP is about 5 t/ha/yr (Jordan 1989, Uhl and Jordan 1984). However, since N_{i0} was set quite high (above the inflection point on the logistic curve), the calculated NEP (dN_i/dt from Equation 3.2-4) was much less than the potential maximum (at the inflection point). An artificially high value of 16 provided an initial NEP that ranged from about 8 to 12 t/ha/yr, depending on the scenario. Although this is still quite high compared with the preferred value of 5 t/ha/yr, tropical NEP declined rapidly to less than 5 t/ha/yr after about 10 years, as the forest organic carbon approached carrying capacity. The sensitivity analysis for this parameter was, therefore, extended to an unrealistically broad range of values from high to low. It is important to enforce some duration of high aboveground NEP on tropical forests. Equation 3.2-5 produces a rapid decline in dN_i/dt due to modulation by the carrying capacity, K, under an equilibrium double-CO_2 climate. We do not expect climate to equilibrate at double CO_2 but rather to continue warming. Thus, tropical expansion could continue at a high rate for some time.

3.2.2 Results

The terrestrial carbon emission trajectories under the four climate scenarios with baseline initial conditions and parameters (Table 3.2-1) are presented in Figure 3.2-1. The UKMO scenario is the most extreme in extratropical change and the least extreme in tropical change. The OSU model exhibits the least extratropical change and the greatest tropical change. The GFDL and GISS results'are intermediate, with GFDL being the more extreme of the two in the extratropics. The accumulated emission pulse from the extratropics ranged from about 60 to 130 Gt of carbon released, or about 1 to 2 Gt/yr. The maximum accumulation of CO_2 in the atmosphere occurs at about 60 years, after which the pulse declines. If the Box model is correct and tropical forests decline under double-CO_2 conditions, the tropics would become an additional source and would increase the size of this carbon pulse.

Table 3.2-1.   Initial Conditions and Parameter Values (all units are for aboveground organic carbon)

Fraction of organic C burned	f	10 %
Decay Rate, post-burn organic C	k	0.05 /yr
Duration of change	n	50 years
NEP, Extratropical	max dN/dt	2 t/ha/yr
Initial Extratropical organic C	$Ni0$	0.4 kg/m^2
NEP, Tropical[1]	max dN/dt	16 t/ha/yr
Initial Tropical organic C	$Ni0$	9.9 kg/m^2

[1] The preferred value is about 5 t/ha/yr (Jordan 1989, Uhl and Jordan 1984).

UKMO, Transient Carbon Pulse
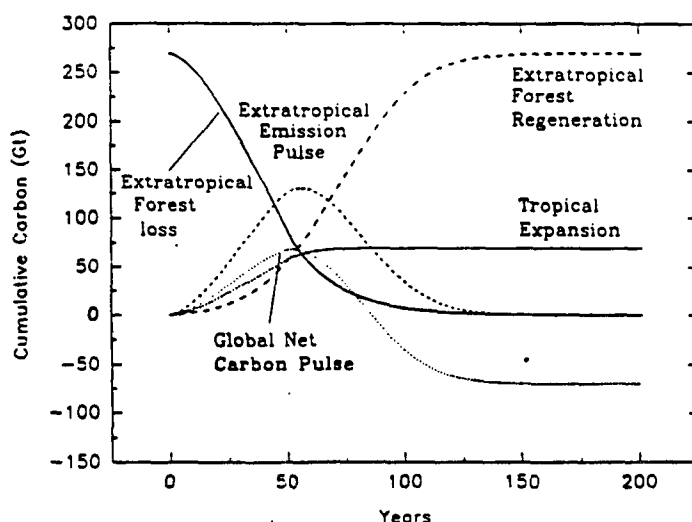
Figure 3.2-1 (a)

OSU, Transient Carbon Pulse
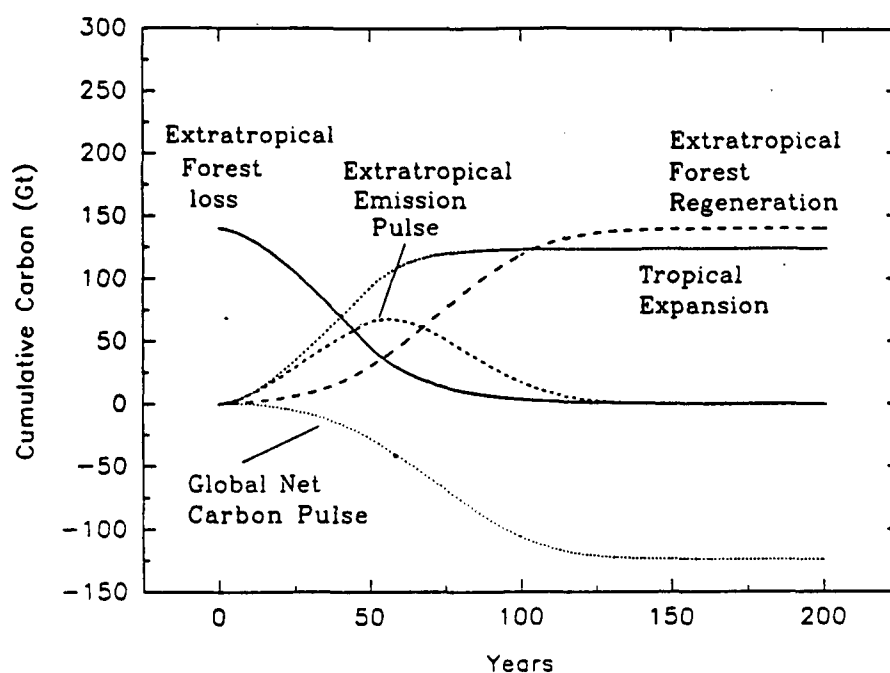
Figure 3.2-1 (b)

GFDL, Transient Carbon Pulse
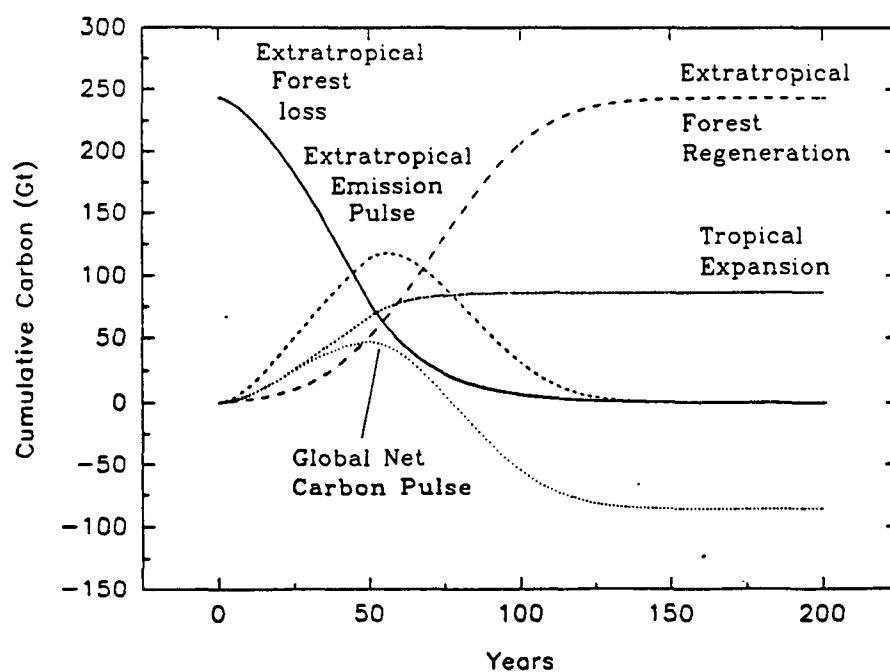
Figure 3.2-1 (c)

GISS, Transient Carbon Pulse
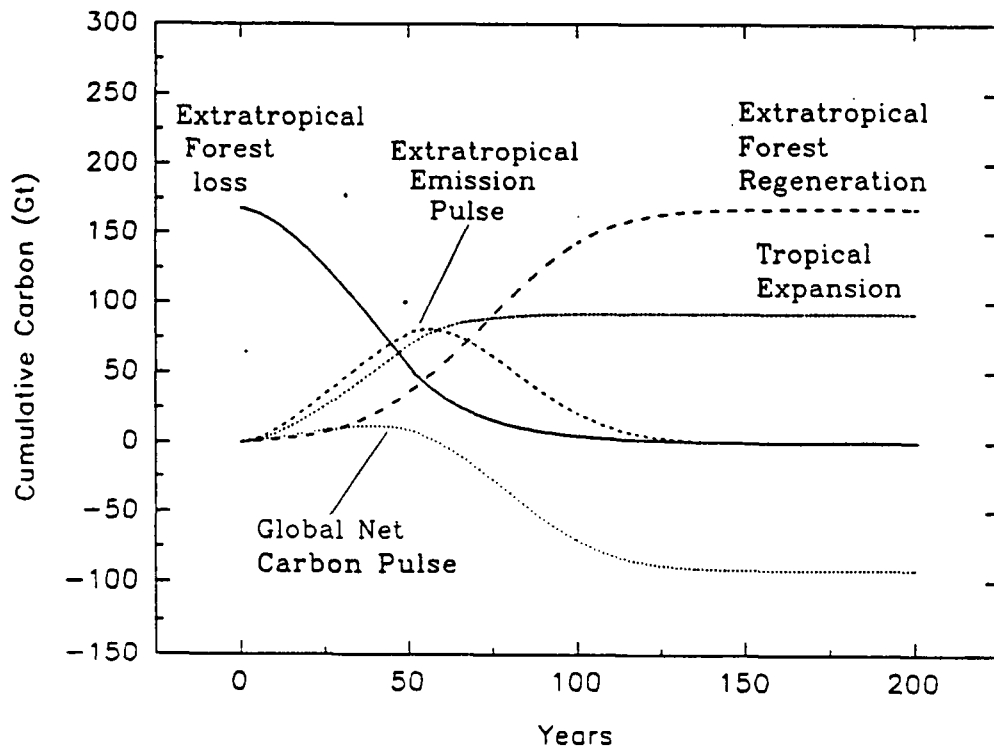
Figure 3.2-1. Transient carbon pulse with the a) UKMO, b) OSU, c) GFDL, and d) GISS GCMs. The trajectory of forest loss (solid line) is the total aboveground organic carbon remaining in the original extratropical forests after annual fire and subsequent decay of remaining biomass according to Equations 3.2-2 and 3.2-3. Forest Regeneration is the cumulative gain of extratropical aboveground organic carbon, post-fire, according to Equations 3.2-5 and 3.2-6. The Emission Pulse is the extratropical pulse of carbon produced by the imbalance between forest loss and forest regrowth. Tropical Expansion is the cumulative growth of tropical forests above current levels of aboveground organic carbon according to Equations 3.2-5 and 3.2-6. The Global Net Carbon Pulse is the Emission Pulse diminished by the Tropical Expansion. All values on the vertical axis are cumulative over time.

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According to the Holdridge model, which predicts tropical expansion, approximately 60 Gt (UKMO) to 125 Gt (OSU) carbon are sequestered over time (Figure 3.2-1, indicated by the negative global net carbon equilibrium). The large expansion of the tropics and the small extratropical change combined in the OSU scenario to completely offset the extratropical emissions of CO_2 However, under the UKMO scenario, the combination still produces a net pulse of about 75 Gt, that is, more than 1 Gt/yr over about 50 years.

3.2.3 Sensitivity Analyses

The magnitude of the extratropical carbon pulse, both in isolation (Figure 3.2-2) and as diminished by tropical expansion (Figure 3.2-3), was examined over a range of parameter values to determine parameter sensitivities. Each parameter was tested individually with the remaining parameters set to the values in Table 3.2-1. The magnitude of the carbon pulse was the only variable recorded. The duration of the pulse near peak values varied considerably under the different parameter values, ranging from about a decade (Figure 3.2-2) to a century or more, and it should be more thoroughly examined. The extratropical pulse was analyzed separately from the global net pulse (which includes a tropical expansion) in order to estimate the sensitivity of the parameters under a tropical decline as projected by the Box model. We did not examine the carbon dynamics of a tropical decline, which presumably would exacerbate the extratropical carbon pulse. Recall that in the extratropics the Box and Holdridge models perform about the same.
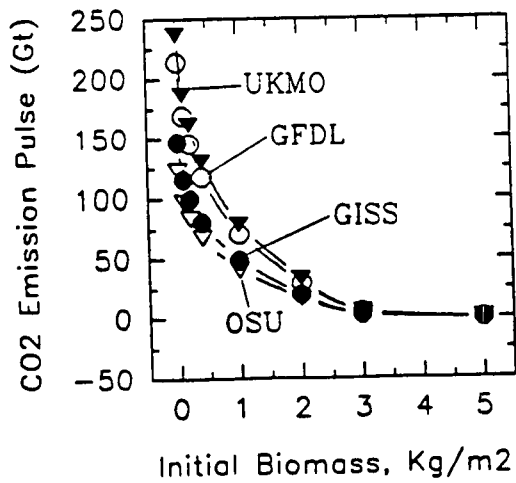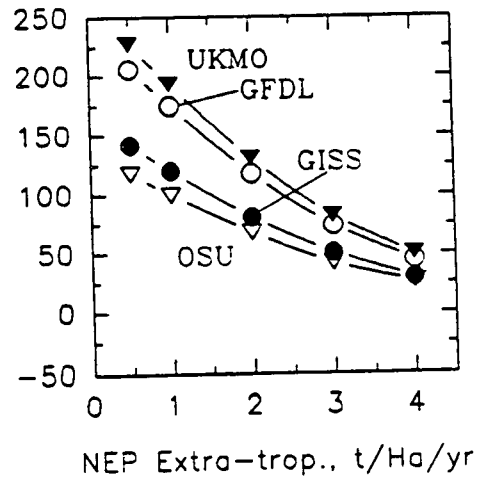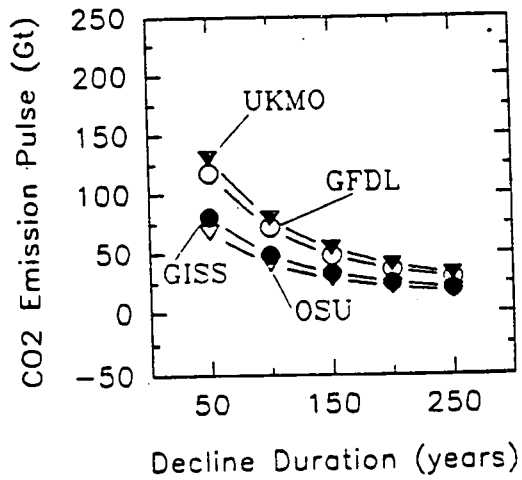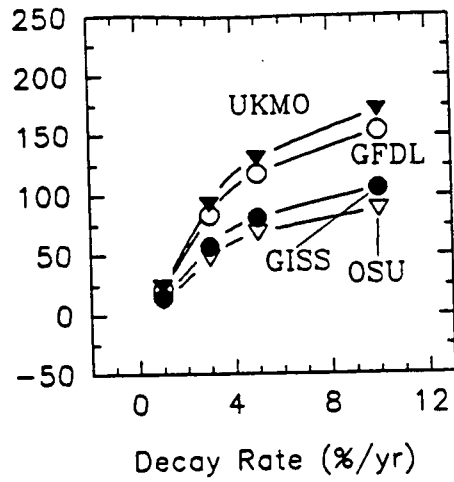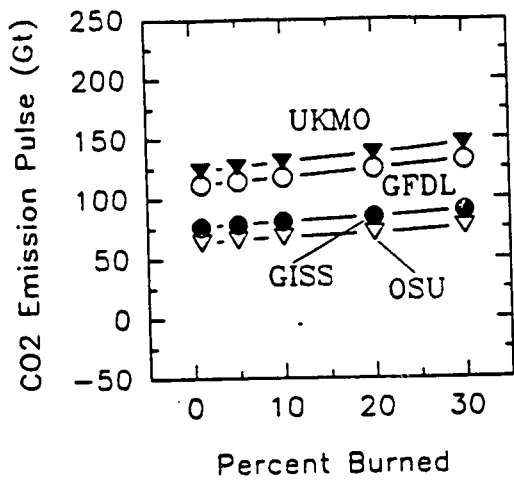
Figure 3.2-2. Sensitivity of extratropical emission pulse to key parameters. Baseline parameter values are in Table 3.2-1.
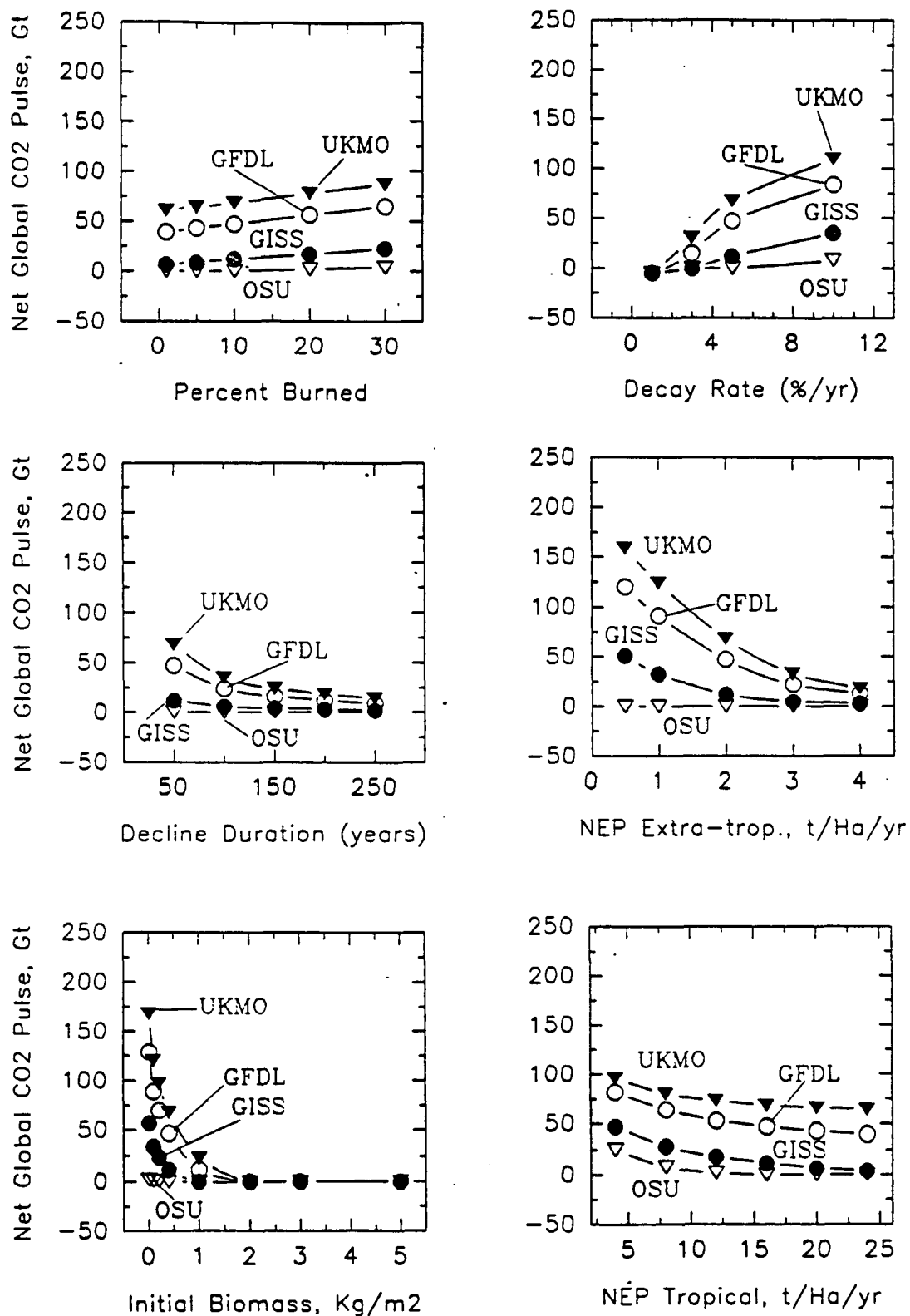
Figure 3.2-3. Sensitivity of global net carbon pulse to key parameters. Baseline parameter values are in Table 3.2-1.

The size of the global carbon pulse was rather insensitive to variation in the percentage of aboveground organic carbon initially burned (Figures 3.2-2a and 3.2-3a). However, the decay rate of the remaining organic carbon is a critical parameter. The range of literature values is about 0.03 to 0.05/yr. In that range the carbon pulse can vary by about 40 Gt (Figures 3.2-2b and 3.2-3b).

The duration, or rapidity, of change is a very important parameter. The slower the change (i.e., the greater the duration), the more capable is the biosphere of keeping pace with the change. The size of the carbon pulse is very sensitive to small changes in duration over the range of 50 to 100 years. If the tropics expand (Figure 3.2-2c), this parameter is less critical than if the tropics decline (Figure 3.2-3c). Under the UKMO scenario, the variation in the size of the carbon pulse with a shift from a 50- to 100-year duration is about 35 Gt with tropical expansion and over 50 Gt with a tropical decline.

A 50% increase in maximum NEP, from 2 to 3 t/ha/yr of carbon, is about equivalent to a 50-year increase in the duration of forest decline; that is, about a 35-Gt decrease in the pulse with tropical expansion (Figure 3.2-2d) and an over 50-Gt decrease without tropical expansion (Figure 3.2-3d).

The magnitude of the carbon pulse was very sensitive to the amount of post-fire organic carbon that represents the new flush of aboveground vegetation on which all future growth depends (Figures 3.2-2e and 3.2-3e). The initial value of 0.4 kg/m^2 of carbon, representing about two years of maximum productivity, is in an extremely sensitive range for this parameter, but this value has been observed (AuClair 1985). An increase in this parameter to 1 kg/m^2, about 10% of the pre-fire organic carbon, would drop the carbon pulse by about 45 Gt with tropical expansion and by over 50 Gt without tropical expansion. This parameter is very sensitive at low values because it places the starting point on the logistic curve further out on an asymptote, effectively producing a large lag before rapid growth ensues. AuClair (1985) examined a sequence of boreal forest stands of varying age post-fire and found an initial organic carbon quite close to our parameter value. He also observed that significant tree growth and organic carbon accumulation required about three decades to begin. Our model produces very similar behavior, with regrowth organic carbon increasing rapidly after about three decades (Figure 3.2-1).

If the tropics expand, the rate of tropical growth (NEP) is sufficiently high for further increases in growth to have little effect on the size of the carbon pulse (Figure 3.2-2f).

If all parameter values were to combine for the most benign yet still reasonable combination, the carbon pulse for the most extreme scenario (UKMO) is much reduced (Table 3.2-2). The parameters were set to 100 years duration, 3 t/ha/yr for extratropical NEP, 1 kg/m^2 initial, post-fire organic carbon, 5% initial

incineration, and 0.05/yr decay rate. A high NEP was used for the tropical forests. Under this combination, the global net carbon pulse with tropical expansion was reduced from 68 Gt to 1 Gt of carbon, and with tropical decline (i.e, extratropical pulse only) from 131 Gt to 16 Gt carbon (Table 3.2-2). These values could be considered a conservative boundary on the transient behavior of these forests. The actual transient response would not likely be this conservative. The same parameters with the most benign model (OSU) produced similar results. Under severe values for the parameters (duration 50 yrs, 1.5 t/ha/yr extratropical NEP, 0.4 kg/m² initial, post-fire organic carbon, 20% incineration, 0.05/yr decay rate, 8 t/ha/yr tropical NEP), the carbon pulse could be as high as 166 Gt (almost 3 Gt/yr) or as low as 15 Gt, depending on the scenario (OSU or UKMO) and on whether the tropics expand or contract.

Table 3.2-2. Range of CO_2 Cumulative Pulse to the Atmosphere under Benign and Severe Model Parameter Values, Assuming Tropical Expansion (Global) and No Change in Tropical Sequestering (Extratropical)

| Parameter Values | Carbon Pulse (Gt) | | | |
| | OSU | | UKMO | |
	Global	Extratropical	Global	Extratropical
Benign	0	8	1	16
Severe	15	86	111	166

3.2.4 Discussion

Depending upon the vegetation scenario (i.e., either expanding or contracting tropics) and the climate scenario (i.e., either more like OSU or more like UKMO), the range of the carbon pulse from aboveground organic carbon only could be anywhere from 0 Gt to about 130 Gt, under the standard parameter values (Table 3.2-1). These estimates are conservative in that consideration of the forest floor and soil organic carbon pools would likely raise the estimate considerably. Fires that penetrate the duff in the boreal forest can release as much as 2 kg/m² of carbon (Johnson and van Cleve personal communication). Additional decay from higher soil temperatures and drier sites could elevate the numbers even more.

The carbon pulse would potentially peak in about 50 to 60 years under the 50-year scenario. In general, there is a tradeoff between the size of the peak and its duration. We did not examine this tradeoff in detail. However, under parameter values that extended the time frame, the pulse was also extended,

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albeit with a correspondingly lower amplitude. The residence time of the excess CO_2 in the atmosphere is likely to be of importance to global climate dynamics.

An attribute of the model that is clearly artificial is the implication of an equilibrium endpoint. Double-CO_2 scenarios are only convenient mileposts with which to gauge relative magnitudes and rates of change. The double-CO_2 point should actually be viewed as a point on a trajectory that may continue to increase. More important, the biome response to double-CO_2 is potentially extreme enough to produce an almost 90% spatial displacement of extratropical forests under some scenarios. If the biogeographic response exceeds that discussed here, the change zone would extend through the entire current distribution and beyond into the change zone of the neighboring biome. This would bring on a whole new set of dynamics. Solomon (1986) predicted just such shifts with successional communities being repeatedly reset to the early succession of a different forest type. Since the model presented here terminates with an equilibrium condition, interpretation of the transient dynamics should be restricted to the period encompassing the ascending phase of CO_2 emission from the extratropics. After that the dynamics become increasingly dominated by the ecosystems approaching carrying capacity.

The direct influence of higher CO_2 levels on plant processes could affect these ecological scenarios. As will be discussed in Section 4, the direct effects of CO_2 include accelerated growth and increased WUE (Strain and Cure 1985). Faster growth rates have been examined as a part of the sensitivity analysis. Due to currently high productivity rates, virtually nothing would be gained, with regard to minimizing the carbon pulse, by increased growth rates in the tropical forests (Figure 3.2-2f). Increased growth rates in the extratropics could, however, offset the impacts of climate change to some degree (Figures 3.2-2c and 3.2-3c).

The most important direct effect of increased CO_2 could be increased WUE. The phenomenon has been observed at the level of the whole plant, but it has not been well explored at landscape scales under limiting water conditions (see Section 4.2). At large spatial scales, radiation may be more important than stomatal processes in the control of landscape water balance (Cowan 1965, Federer 1982, Jarvis and McNaughton 1986). These uncertainties require further research. However, should increased WUE prove important at large scales, it could mitigate the decline process directly and potentially preclude any significant dieback and disturbance regime. For these benefits to accrue, the physiological response must precede the gradually increasing climate stress. Since both increasing stress and increasing WUE are consequences of a gradual increase in CO_2, it is uncertain which effect, biotic or climatic, would manifest itself most rapidly. If increased WUE lags behind climate-induced stress, it may occur too late for significant benefit.

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If a maximum pulse of carbon is considered to be about 130 Gt over about 50 years, annual emissions of carbon could increase by about 2.6 Gt per year. This would be about a 37% to 43% increase in annual emissions of carbon, some of which would be sequestered by the oceans and the terrestrial biosphere (Keeling et al. 1989, Harvey 1989, Tans et al. 1990). The potential effect of this positive feedback to the climate system would be to increase the rate of change of climate, which in turn could further stress natural ecosystems.

The process of CO_2 release from the biosphere through fire is, of course, not completely efficient. Organic carbon will be oxidized to CO_2, carbon monoxide, and other organic compounds, depending on the conditions of combustion (Cofer et al. 1989). Incomplete combustion could reduce the size of the CO_2 pulse, but it could also produce other consequences. Carbon monoxide is important in tropospheric chemistry relative to ozone, methane, and hydroxyl radical (Crutzen 1988). Injections of particulates from fires over a prolonged forest decline could also produce feedbacks to the climate (Harvey 1988). Nitrous oxide released from burning green leaves could act as an additional positive feedback to climate warming (Cofer et al. 1989, Westberg et al. 1981, Stith et al. 1981).

In summary, the transient response of the biosphere to climate change could produce a positive feedback to the changing climate by mobilizing terrestrial carbon at a faster rate than it can be withdrawn by emerging vegetation. A significant uncertainty in this scenario is the response of the tropics, which could expand or contract. These uncertainties exist for both the biosphere modeling and the climate scenarios.

Our results suggest that the transient dynamics of the biosphere could be quite different from those inferred from equilibrium considerations. Recall that under equilibrium comparisons, a warmer, wetter world tends to support more aboveground biomass and is therefore considered to be a net sink for carbon (Section 3.1). Apparently the only circumstances under which the terrestrial biosphere might behave as a carbon sink under transient conditions are when either the rate of climate change is slow or the magnitude of the change is relatively small, or both. If either the rate or magnitude of change is sufficiently extreme, ecosystem rate processes are likely to be exceeded, resulting in catastrophic forest decline in the extratropics. Double-CO_2 equilibrium scenarios are only considered as a convenient milepost on a continuous trajectory of CO_2 increase. Actual atmospheric equilibrium conditions for CO_2 are not expected to occur for some considerable time after doubling. Therefore, even our transient analyses that carry the biosphere to an equilibrium are conservative with regard to eventual changes that could occur. The occurrence of the likely driver of the transient decline of forests, drought followed by fire, must be a high priority for future research.

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Bonan et al. (1990) completed a sensitivity analysis of a detailed boreal forest computer model. They found that the forests were very sensitive to increases in PET, which produced soil drying and greatly increased the probability of fire. The stress due to increased PET could be offset if precipitation increased sufficiently. However, projected increases in precipitation by the GCMs in boreal regions are not likely to sufficiently offset the rather larger increases in PET due to large increases in temperature (Bonan et al. 1990, Grotch 1988). These results are consistent with the dynamics presumed here and elsewhere (Solomon 1986).

The most sensitive parameters in the model presented here were the rates of aboveground NEP in extratropical forests, the decay rate of post-fire debris, and the amount of initial live organic carbon post-fire. The form of the logistic equation may not be appropriate for the earliest stages of ecosystem recovery. Measuring early successional rates of NEP should be a priority research area to refine the form of the equation. The potential mitigating influence of direct CO_2 effects and the timing of those effects relative to the timing of potential drought should also receive attention. It is apparent from these analyses that the potentially rapid rate of climate change is perhaps the overriding factor producing catastrophic ecosystem responses with ensuing positive feedbacks to global warming. This work underscores the importance of slowing the rate of climate change as recommended by Lashof and Tirpak (1989). Most approaches to limiting the rate of climate change focus on limiting anthropogenic emissions of CO_2 and other radiatively important trace gases. However, large-scale ecosystem manipulation to sequester carbon, reduce drought effects, establish appropriate species, mitigate impacts on surface and near-coastal waters, and alleviate atmospheric pollution from large, persistent forest fires could be important in limiting positive feedbacks from the biosphere and in optimizing the biospheric responses to climate change.

3.2.5 Research Needs

Future research priorities ensue from these analyses and can be grouped into several categories. The most critical assumption is that forests will decline due to drought stress and will eventually burn. This assumption should receive considerable scrutiny through focused research efforts on regional water balance, CO_2-induced changes in WUE, and climate-fire interactions. Given this assumption, the most critical processes are decomposition rates of coarse, woody debris, and post-fire biomass and regrowth rates as determined by successional processes. Mitigation options to reduce forest decline, sequester carbon, and facilitate regrowth should receive attention. All three of these areas, i.e., decline processes, regrowth processes, and mitigation processes, must be examined in the context of current and anticipated land use practices.

The research needs may be summarized as follows:

1)   Processes of forest decline and disturbance regimes; in particular:
   - Interaction of CO_2 concentration, WUE and landscape water-balance processes
   - Climate, drought stress, pest, fire dependencies

2)   Post-disturbance regrowth and succession, specifically:
   - Post-fire biomass and regrowth rates
   - Dependencies of regrowth dynamics on species and life-form composition during succession

3)   Mitigation options for:
   - Stress detection (monitoring), stress amelioration (e.g., thinning)
   - Regrowth enhancement (e.g., selective 'weeding', introductions)

Despite the prominent role of the terrestrial biosphere in the global carbon cycle, limited information is available on long-term response of vegetation to CO_2 enrichment. This lack of knowledge is incongruous with the readily quantified and widely accepted increase in atmospheric CO_2 that has occurred since the turn of the century. Preliminary results from studies of two ecosystem types, arctic tundra and a coastal marsh, reveal that long-term system responses to increases in CO_2 vary depending on site conditions and plant genotype (Oechel et al. 1984, Drake et al. 1987, Tissue and Oechel 1987, Curtis et al. 1989b, Mooney et al. *in press*). Long-term field evaluations of forest ecosystem response to CO_2 enrichment have been initiated only in recent years.

4.1   Trees

The ability of individual trees to sequester carbon will change with increasing atmospheric CO_2 concentrations and subsequent climate change (moisture and temperature stress). A rise in atmospheric CO_2 concentration is the most certain of projected global changes and thus it will be considered first.

4.1.1 Effect of CO_2 Enrichment on Plant Development

To understand direct and indirect effects of CO_2 enrichment on individual trees requires knowledge of how juvenile and mature trees assimilate and allocate carbon during ontogeny. This entails both: 1) a summation of seasonal patterns in growth and development; and 2) an annual adjustment to these seasonal patterns due to inherent changes in plant physiology with age. The current understanding of CO_2 effects on trees and forests is based almost exclusively on studies using tree seedlings measured during one growing season. Preliminary studies on the response of arctic and salt marsh (C_3 and C_4) annual plants to CO_2 enrichment have also been completed (Table 4.1-1). The seedling response literature contains little information on seasonal growth patterns or changes in those patterns over time. Furthermore, seedling research has been conducted almost solely in controlled-environment chambers where growth conditions, and therefore responses, can be artificial. Long-term measurements of forest ecosystem response to CO_2 enrichment under realistic conditions are sorely needed.

Despite the limitations imposed by artificial environments and short study durations, these studies have consistently demonstrated many positive changes in growth, morphology, and physiology in woody plant due to increased atmospheric CO_2 concentrations (Table 4.1-2). Indeed, commercial seedling production facilities have utilized enriched-CO_2 environments for decades to enhance growth rates (Tinus

and McDonald 1979). The following summary briefly reviews these potential direct effects of CO_2 on seedling growth, morphology, and physiology. Additional reviews are available in Strain and Cure (1985), Shugart et al. (1986), Kramer and Sionit (1987), and Allen (1990).

Table 4.1-1   Summary of Arctic and Salt Marsh (C_3 and C_4) Annual Plant Responses to Enriched CO_2 Environments in Field Exposure Chambers (from Mooney et al. *in press*)

I. Plant Effects	Response to CO_2 Enrichment[1] Arctic	Saltmarsh C_3	C_4
Carbon exchange			
Photosynthesis	0	+	0
Photosynthetic acclimation	+	0	0
Plant respiration	0	-	-
Shoot decomposition	n/a	-	-
Growth			
Shoot expansive growth	0	0	0
Root biomass	-/0	+	0
Number of shoots	+	+	0
Size of shoots	0	0	0
Root/shoot ratio	-/0	+	0
Tissue Composition			
Nitrogen concentration	-	-	0
Carbon/nitrogen	+	+	0
Starch content	+/0	n/a	n/a
Tissue density/specific wt.	+	0	0
Salt content	n/a	-	n/a
Development/Reproduction			
Senescence	-	-	-
Tillering	+	+	0
Number of flowers	-	0	0
Number of seeds/stem	-	0	0
Sexual/asexual reproduction	-	n/a	n/a
Water Use			
Transpiration	0	-	-
Water use efficiency	0	+	+
Leaf temperature	0	+	+
Water potential	n/a	+	+

Table 4.1-1 (cont'd)

| | Response to CO_2 enrichment | | |
| | Arctic | Saltmarsh | |
		C_3	C_4
II. Ecosystem effects			
Evapotranspiration	0	-	-
Net carbon storage	+/0	+	+
Carbon exchange acclimation	+	0	0
Net ecosystem respiration	-/0	-	-
Species composition	+	n/a	n/a
Water use	0	-	-
Nitrogen content of canopy	n/a	0	0
Soil enzyme activity	+/-	n/a	n/a
Soil solution nitrogen	-/0	n/a	n/a
Nitrogen content of below-ground biomass	n/a	+	0

[1] Relative to ambient concentrations; +, increase; -, decrease; 0, no change; n/a no data available

Table 4.1-2 Seedling Morphological and Physiological Responses to Enriched-CO_2 Environments Based on Short-term Controlled-Environment Studies ($\leq$ 1 yr, with an exception as marked)

Morphology	Response[1] Conifer	Broadleaf
stem diameter	+	+
stem height	+	+
relative growth rate	+	+
root and shoot weight	+	+
weight:height ratio	+	n/a
root:shoot ratio	+	+/-
fine:coarse root ratio	+	n/a
N-fixing nodule mass	n/a	+
mycorrhizal mass	+	+
number of branches	+	+
secondary leaf production	+	n/a
crown width	+	n/a
leaf area	+	+
leaf area:total biomass ratio	n/a	+
leaf thickness	+	+
leaf area duration	+	+
stomatal density	n/a	+
number of buds	n/a	+
weight per bud	n/a	+
wood density	n/a	+

Physiology

	Conifer	Broadleaf
net photosynthesis	+	+
starch in needles	+	n/a
allocation of carbon to roots	+	n/a
pigment concentrations	-	-
chlorosis[,2]	+	n/a
stomatal conductance	-	-
water use efficiency	+	+
water content/potential	-	n/a
leaf temperature[2]	+	n/a
heat tolerance[2]	-	n/a
nitrogen concentrations	n/a	-
nutrient uptake	+	+
nutrient use efficiency	+	+
ion leaching from soil	-	n/a

[1] +, increase; -, decrease; n/a, no data available
[2] based solely on a multi-year study

4.1.1.1 Seedling growth responses to CO_2 enrichment

Table 4.1-2 shows that higher carbon assimilation rates resulting from a reduced CO_2 gradient between the leaf and atmosphere in an enriched-CO_2 environment (all other things being equal) lead to:

1)   increased growth rates of roots to capture and maintain soil contact for water and nutrient uptake (Tolley and Strain 1984b, Sionit et al. 1985, Brown and Higginbotham 1986, Norby et al. 1986a, Hollinger 1987, Norby 1987, Norby et al. 1987, Campagna and Margolis 1989);

2)·   increased stem and foliar biomass, surface area, and foliage duration for photosynthetic surface and competition for light (Funsch et al. 1970, Tinus 1972, Canham and McCavish 1981, Rogers et al. 1983a,b, Tolley and Strain 1984a,b, Higginbotham et al. 1985, Oberbauer et al. 1985, Brown and Higginbotham 1986, Norby et al. 1986b);

3)   increased bud size and weight for ensuing years' growth (Norby et al. 1986a); and

4)   more available carbon for metabolite synthesis (e.g., starch and sugar) for stress resistance and symbiotic associations (Norby 1987, Norby et al. 1987, O'Neill et al. 1987b, Arnone and Gordon *in press*).

In addition, the optimal temperature for photosynthesis increases (Kramer and Sionit 1987) and the light compensation point decreases with increasing CO_2 concentration, suggesting that plants can maintain photosynthetic rates at higher temperatures and lower light levels in higher CO_2 environments. Plants do not respond above a threshold CO_2 level of about two- to three-times ambient CO_2 concentrations (Higginbotham et al. 1985, Rogers et al. 1983a). Loblolly pine (*Pinus taeda*) is a notable exception to these generalities, showing no short-term increase in biomass accumulation due to increased CO_2 (Tolley and Strain 1984b).

Seedlings respond physiologically to CO_2 enrichment typically within hours to days of their introduction to a high-CO_2 environment, with some acclimation to higher CO_2 concentrations within weeks to months. For example, arctic plants under field conditions (Tissue and Oechel 1987) and temperate plants in growth chambers (Tinus 1972, Tolley and Strain 1984a) show the loss of growth responses within a growing season. This latter "acclimation" (in temperate plants) may be attributed to saturation of the carbon sink in a limited environment (e.g., pot-bound plants). Examination of CO_2 acclimation *in situ* with coastal marsh grasses suggests that responses will vary widely by site and plant genotype (Curtis

et al. 1989a). The response of plants that are first acclimated to a high-CO_2 environment and then placed in an environment that is further enhanced with CO_2 is unknown.

Information on the growth characteristics of woody perennials that are exposed to enriched-CO_2 environments from the time of seed germination is also limited. A study at ERL-C with three native tree species has shown little morphological difference in plants at 14 weeks from germination (growth responses of one of three species, *Acer macrophyllum*, are shown in Table 4.1-3). Research will proceed through consecutive growth and dormancy cycles to determine if anatomical, morphological or physiological differences develop that prepare the seedlings for overwintering and ensuing years' growth. This study is the first to examine multiple-season ontogeny of seedlings and to expose the *Acer* genus to enriched CO_2.

Table 4.1-3.   Early Growth (14 weeks) of Acer macrophyllum Seedlings (n = 48) in Ambient- and Enriched-CO $_2$ Environments (350, 575, and 700 ppm)

CO_2 Concentration (ppm)	Collar diameter (mm)			Seedling Height (cm)		
	Mean	Std	Range	Mean	Std	Range
350	5.7	1.0	3.1-7.5	67.0	14.2	27.0-89.7
575	6.4	0.9	3.6-7.8	78.4	14.7	30.7-101.9
700	6.7	0.7	4.9-7.9	76.7	12.7	49.3-99.4

Long-term studies with juvenile trees reported by Surano et al. (1986) and Houpis et al. (1988) have only partially evaluated issues regarding the duration of short-term responses. These reports are based on a 2.5-year experiment with tree saplings grown in individual field chambers. This study demonstrated the loss of many of the positive short-term responses noted in Table 4.1-2, and it also revealed negative long-term plant responses. For example, seedlings tended to accumulate heat energy in leaves due to partial stomatal closure. Surano et al. (1986) reported a general decrease in heat tolerance (i.e., in the upper thermal limits of the photosynthetic apparatus) with increased CO_2 concentrations even though the optimum temperature for photosynthesis is increased. Foliage showed classic visual stress symptoms (e.g., chlorosis), and saplings showed eventual decreases in growth rates (relative to control treatments) after early accelerated height and diameter growth advantages.

Based on these results, Surano et al. (1986) and Houpis et al. (1988) proposed that plants reached a new homeostasis under higher CO_2 and lost the short-term benefits as environmental stresses developed. However, these results are from one study conducted under one set of conditions on one plant each. Additional multiple-year exposure studies are clearly needed to evaluate tree responses for a range of biomes and environmental conditions.

4.1.1.2 Ecophysiological responses to CO_2 enrichment

The literature provides a preliminary picture of potential nongrowth-related effects of CO_2 on woody plants, including: modification of water- and nutrient-use efficiencies, stress tolerance, and plant dormancy requirements. Water-use efficiency (WUE) is defined as a ratio, the number of CO_2 molecules fixed per water molecules transpired. As CO_2 concentration increases, fewer water molecules exit the stomata for each CO_2 molecule that enters. Thus, plants may either put on more biomass while using a fixed amount of water, or they may use less water to acquire a fixed amount of biomass. As with growth responses, the largest changes in WUE are seen early in the enrichment period (Norby and O'Neill 1989), a potentially important time given the synchrony of water availability and plant growth cycles.

An increase in nutrient-use efficiency appears to stem almost solely from increased biomass production with little to no increase in nutrient uptake, interpreted as a nondamaging foliar dilution of elements. Normally deficient elements such as phosphorus, potassium, magnesium, and boron may be recycled internally to new meristems in enriched-CO_2 environments (Luxmoore et al. 1986). Increased fine root growth in a higher CO_2 atmosphere enhances the nutrient availability in a given soil profile. Finally, improved water- and nutrient-use efficiencies of plants in a CO_2-enriched environment have the potential to significantly enhance seedling performance on nutrient- and water-limited lands.

The influences of CO_2 enrichment on biotic and anthropogenic plant stresses other than water or nutrient deficits could be significant, but they have not been fully considered (Kramer and Sionit 1987). For example, insect damage to plants is reduced and parasites grow more slowly and suffer greater mortality in higher CO_2 atmospheres (Fajer et al. 1989). These effects are linked with reduced nutrient content (nitrogen content or carbon:nitrogen ratio) and water content in host material. Fajer et al. (1989) found no change in the levels of defensive compounds produced by plants. Air pollution injury is likely to be reduced with increasing CO_2 due to partial stomatal closure (Green and Wright 1977). However, as with growth data, only short-term changes in stress responses due to increased CO_2 concentrations have been tested. Long-term, multiple growing season research is required.

Carbon dioxide enrichment may also alter the natural dormancy cycle of trees (Bailey et al. 1990), creating potential reproduction and growth problems (e.g., frost damage to unhardened plants). A short-term study by Rogers et al. (1983a) revealed that pine trees in high-CO_2 environments may continue active growth after trees in ambient chambers become dormant, an effect similar to that found with over-irrigation or over-fertilization. Enriched CO_2 has been shown to alter carbohydrate storage patterns (particularly starch). Starch accumulation (the storage of energy for overwintering and bud break) is related directly to plant dormancy and stress resistance. Oberbauer et al. (1985) demonstrated excess starch accumulation in chloroplast in foliage of tropical tree species, and Campagna and Margolis (1989) showed increased starch in the needles of black spruce with increasing CO_2 concentrations. Finally, higher leaf temperatures, which may interfere with temperature control of dormancy initiation, have been observed in high-CO_2 environments. The fate of growing season responses (e.g., starch accumulation and extension of the season) later in the plant's growth cycle (during dormancy) is unknown, as is their effect on subsequent years' growth.

The interaction of direct CO_2 enrichment effects and indirect climate change effects must also be considered. Section 1.4.3 of this report demonstrated the potential for increased atmospheric CO_2 concentrations to induce changes in climate, primarily in moisture and temperature. Ecophysiological plant responses to CO_2 may either offset or amplify these effects. For example, decreased water availability for trees could be offset by increased WUE, but changes in water movement through plant stomata might interfere with temperature regulation. A temperature increase would complement CO_2 increases in terms of increased carbon assimilation rate (given an increase in the temperature optimum for photosynthesis), but it may also interfere with bud dormancy regulation and winter cold-hardiness. The potential interactions are numerous and must be addressed regionally as projections of climate change are refined.

4.1.2 Water-Use Efficiency

Increases in WUE due to increasing atmospheric CO_2 concentrations represent the potential for substantial impacts on forest ecosystem condition, composition, and migration. Unfortunately, our knowledge of this process is largely limited to growth chamber studies under non-limiting conditions of water availability. It is not clear what benefits could accrue from increased WUE if soil water availability is decreased or if the demand for water (PET) is increased (Neilson et al. 1989). The response of forests to changes in regional distribution of precipitation in combination with temperature and PET extremes has been considered. For example, Neilson et al. (1989) and Urban and Shugart (1989) concluded that forest ecosystems in the southern United States could experience long-term negative impacts due to

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extended drought in a double-CO_2 climate. The following section addresses predictions regarding changes in seedling and tree water relations in an enriched-CO_2 environment, changes that may modify plant response to an altered climate.

General water relations in plants and adaptation to or tolerance of drought stress in natural and managed ecosystems have been reviewed by other authors (e.g., Kramer 1983, Jarvis 1987).

4.1.2.1 Short-term water-use responses to CO_2 enrichment

Several short-term studies of ecophysiological processes have determined that CO_2 enrichment can alter the water relations of C_3 and C_4 plants. Stomatal conductance is a primary plant process influenced by CO_2 enrichment, and reduced stomatal conductance (lower transpiration per unit leaf area) has been widely observed in plants in enriched-CO_2 environments (Houpis et al. 1987, Williams et al. 1986, Hollinger 1987, Eamus and Jarvis 1989, Norby and O'Neill 1989). The ratio of carbon gain to water loss, one measure of WUE, is consistently increased with elevated CO_2 (Rogers et al. 1983a,b, Oberbauer et al. 1985, Norby et al. 1986a, Conroy et al. 1988, Norby and O'Neill 1989). This phenomenon has been demonstrated with instantaneous as well as cumulative measurements of water use (Morison 1987, Mooney et al. *in press*). However, instantaneous WUE response can be reduced at the whole-plant level or over long periods of adjustment to CO_2 enrichment (Morison 1987).

An examination of arctic and estuarine plants subjected to CO_2 enrichment over the long term suggests that changes in anatomy and other ecophysiological processes contribute to changes in plant water relations, as reviewed by Mooney et al. (*in press*). For tree seedlings, Norby and O'Neill (*submitted*) observed that the ratio of leaf area to dry weight decreased and root biomass increased in yellow-poplar *(Liriodendron tulipifera)*, enhancing WUE under CO_2 enrichment. Research has demonstrated that mycorrhizal development and root biomass of tree seedlings are significantly increased in a high-CO_2 environment (Norby et al. 1987, O'Neill et al. 1987a). These mycorrhizal relationships can play a prominent role in drought avoidance or tolerance (Dixon et al. 1980).

Changes in WUE in plants observed in short-term controlled- environment studies may not always be observed in the field due to the host of interacting factors that regulate plant development. For example, Tolley and Strain (1985) observed that CO_2 enrichment ameliorated the impact of drought in sweetgum but not in loblolly pine. Plants resist drought through tolerance and avoidance mechanisms (Eamus and Jarvis 1989). Tolerance mechanisms include maintenance of cell turgor, and thereby of leaf expansion and photosynthesis, under low water potential. Avoidance includes low stomatal conductance, leaf

abscission and increases in root system biomass. However, plants that avoid drought through high WUE can be at a competitive disadvantage in the field if a drought-tolerant competitor can exploit the more available water for its metabolic processes (DeLucia and Heckathorn 1989).

Plants growing in an enriched-CO_2 environment may efficiently tolerate drought through osmotic adjustment of tissue (Eamus and Jarvis 1989), depending partially on carbon metabolism and source-sink relationships of leaves. Elevated CO_2 increased the concentration of soluble sugars in the feeder roots of loblolly pine under drought stress (Norby *personal communication*). The accumulation of osmotic solutes is linked to the degree of water stress in many conifers. This and other drought tolerance and avoidance mechanisms in plants growing in an enriched-CO_2 environment merit further investigation.

4.1.2.2 Long-term water use responses to CO_2 enrichment

Long-term responses of woody plants to CO_2 enrichment have not been evaluated. Therefore, many research issues focus on understanding long-term tree responses to changes in CO_2 concentration, moisture, and temperature. This will require multi-year exposures and measurements on a diverse spectrum of life stages under field conditions. Research should be designed to explain and model tree responses mechanistically since empirically testing every possible combination of conditions is impossible (Mooney et al. *in press*).

4.1.3 Research Needs

Section 4.1.2.2 noted the almost complete lack of research in the area of long-term seedling and tree responses to CO_2, particularly in the area of whole plant development and WUE. The response of terrestrial vegetation to CO_2 enrichment with or without climate change will have tremendous effects on the global carbon cycle. The following research tasks are needed:

1)   Long-term exposures of tree species from the time of germination until mature tissue is generated.

2)   Assessment of whole-plant development and changes in anatomy, morphology, and physiology, to allow the formulation of process-based models of responses to CO_2 enrichment.

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3)   Characterization of CO_2 effects on WUE for a wide range of genera (e.g., tropical to boreal) and life stages.

4)   Quantification of atmospheric CO_2 enrichment effects on terrestrial carbon pools and fluxes.

4.2   Ecosystem Perspective

The above sections discuss the possible impacts of increased CO_2 concentrations on WUE of individual plants. Increased WUE could counteract the potential negative effects on plant growth of increased PET caused by climate warming and/or declines in precipitation (Mooney et al. *in press*). Whether increased WUE will mitigate the effects of increased PET in forested ecosystems is a key research question debated in the literature (Oechel and Strain 1985, Strain 1987, Norby and O'Neill 1989, Mooney et al. *in press*).

Availability of water appears to be the primary determinant of the distribution of forests in the continental United States (e.g., Neilson et al. 1989, Stephenson 1990). Current forests appear to use nearly all the water available to them during the growing season for growth or simply for maintenance (Neilson et al. 1989). The amount of regional evapotranspiration in forests is a function of the volume of deep soil water, rooting depth, leaf area over the region, and atmospheric vapor pressure deficit. The primary regulator of evaporation from vegetation appears to be leaf area, which increases or decreases over time as water supplies change (Woodward 1987). If regional PET were to increase due to increased temperature (ignoring the direct effects of CO_2 and assuming no change in water supply), soil water would be depleted, causing plants to die or shed leaves. Leaf area and hence evapotranspiration would decrease in subsequent years, until a new biomass equilibrium is reached. If this process were carried to the extreme, either through increased PET or decreased water supply, trees could no longer be supported (Neilson et al. 1989, Stephenson 1990).

What could happen under warmer conditions with increased WUE caused by higher CO_2 concentrations? At least two scenarios are plausible. First, since more water is effectively available for growth, regional leaf area could increase during the growing season in comparison with the unchanged WUE scenario. However, increased leaf area would increase the amount of evapo-transpiration from the ecosystem, with the water available for growth being used before the end of the growing season, as in the unchanged WUE scenario. In fact, increased leaf area could result in faster evapotranspiration, with water stress beginning earlier in the growing season. Net primary productivity need not be any higher

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and could be less than in the unchanged WUE scenario. Changes in species composition would occur as in the unchanged scenario.

A second scenario takes into consideration the possibility that root/shoot allocations could change under higher CO_2 concentrations with proportionately more growth allocated to roots and mycorrhizal associates (Norby et al. 1987, O'Neill et al. 1987b). Root biomass and area can increase up to two-fold under CO_2-enriched environments (Rogers et al. 1983a), with roots potentially reaching deeper into the water table. Under this scenario, leaf area and thus evapotranspiration would not increase as much as in the first scenario. Net primary productivity could increase relative to the unchanged WUE scenario as long as the increase in evapotranspiration caused by the limited increase in leaf area did not offset gains in effective moisture caused by the higher WUE and root biomass. Alternatively, increased root area could simply facilitate the rapid extraction of soil water, again limiting the system (Federer 1982).

If regional ecosystems are to realize a benefit from increased WUE of vegetation, the most effective strategy would be to use less water and not accumulate additional biomass in either root or shoot. However, this seems unlikely, given that plants clearly do not know that they will be water limited until they actually are water limited. Thus, one might expect plants to spend the water and add the extra biomass (in either root or shoot), which could result in drought stress as the water is depleted.

Another issue concerning the direct effects of CO_2 on ecosystem productivity is nutrient availability. If plant growth is limited by nutrients rather than by water, increasing WUE will have minimal impact on plant growth. Experimental data suggest that plants have mechanisms that use soil nutrients more efficiently under elevated-CO_2 conditions, effectively increasing nutrient-use efficiency (Luxmoore et al. 1986, Norby et al. 1986a, O'Neill et al. 1987a,b). Longer term experimental studies with representative forest soils in combination with water stress are needed to determine the effects of elevated CO_2 on natural communities.

Through its role in the carbon cycle, the terrestrial biosphere is one of the major components in global climate dynamics along with the oceans of the world (Schneider 1989b, Houghton et al. 1983). The size of the carbon pool is much greater for oceans than for continents (as shown in Figure 1.1-1, oceans have about 38,500 Gt of carbon versus approximately 2,000 Gt for the terrestrial biosphere). However, the flux rates of carbon in the terrestrial biosphere are approximately equal to those of oceans (Houghton 1987). The terrestrial biosphere, therefore, covering only 30% of the earth's surface, has a much greater carbon flux rate per unit area than the oceans have. This is largely the result of photosynthesis by vegetation in the terrestrial ecosystems (Figure 1.1-2). Forests, in turn, are a substantial component of the terrestrial biosphere (34% of the area), and have a significant influence over terrestrial carbon fluxes into and from the atmosphere (Harmon et al. 1990, Woodwell et al. 1983).

World forests capture and store significant amounts of atmospheric CO_2 through photosynthesis (Shands and Hoffman 1987). Waring and Schlesinger (1985) stated that: 1) "the equivalent of the entire CO_2 content of the atmosphere passes through the terrestrial biota every seven years, with about 70% of the exchange occurring through the forest ecosystems"; and 2) the vegetation and soils of forests combined contain about 60% of the organic carbon in terrestrial ecosystems of the world using the estimates of 765 Gt vegetative carbon and 635 Gt carbon in forest soils (Waring and Schlesinger 1985).

Consequently, forest management to foster forest carbon sequestering is one possible option for mitigating the increase in atmospheric CO_2 concentrations. The purpose of this section is to review management options for increasing carbon sequestering in forested regions, specifically, reforestation and afforestation, forest stand treatment, and management of soil carbon. In addition to summarizing the available literature, new analyses are presented on: 1) the potential amount of carbon that could be sequestered in tropical regions each year through reforestation and afforestation, 2) the amount of land that would have to be available for reforestation in the United States to offset its yearly emission of CO_2, and 3) the effects of thinning and fertilization on forest growth.

5.1 Forest Management Opportunities

Forest management refers to the combination of business methods and forestry principles to forest areas to achieve the land owners' objectives (Barrett 1980, Davis 1966). Components of forest management, while directed at maximizing a specific yield from forest stands (e.g., timber pulp,

recreation) can also alter carbon storage and release from forests. Forest management practices relevant to the mitigation of atmospheric CO_2 increases are reviewed here.

1) Silviculture

Silviculture refers to the biological and physical manipulations of forests based upon ecological principles for the purpose of enhancing yields of wood and other forest outputs (Smith 1986).

Typical silvicultural treatments are:

a) Reforestation: the artificial establishment of forests on land that previously carried forests. Reforestation frequently involves replacing the previous crop by a new and essentially different crop (Wiersum 1984). When essentially the same crop as before is established, the process is sometimes referred to as artificial regeneration (as opposed to natural regeneration or the establishment of new forests by natural means).

b) Afforestation: the artificial establishment of forests on land that previously has not carried forests within anyone's memory or during the last 50 years (Wiersum 1984).

c) Stand treatments: manipulations applied to established plantations or existing forests usually to improve growth and yield of wood or other forest resources. Manipulations include weed control, thinning (i.e., stocking control), and fertilization. This practice is also called timber stand improvement (TSI) or forest tending (Smith 1986, Barrett 1980).

2) Mensuration

Mensuration is the subject of forest stand measurements, commonly conducted to quantify forest inventory (i.e., standing stock), growth, and yield (Dixon et al. 1990, Husch et al. 1972). Mensuration includes assembling data and maps of forest land area. Worldwide, definitive data on the amount of land now occupied by forests or available for reforestation are difficult to obtain (Section 5.1.1). Currently, development of more reliable data bases on this subject is a high research priority.

3) Harvesting Operations

Harvesting refers to the activities required to extract the wood resource from forest lands (Barrett 1980). Activities include road construction, logging methods (e.g., selective or clearcutting), and equipment deployment. This is also the process needed to convert a forest area from one or a mix of species to a forest with a more desirable composition. Unfortunately, harvesting without attempting any reforestation often leads to less productive land uses, i.e., deforestation (Section 5.3), and in some places, desertification.

4) Agroforestry

A current definition for agroforestry is "... a land use that involves deliberate retention, introduction, or mixture of trees or other woody perennials in crop/animal production fields to benefit from the resultant ecological and economic interactions" (MacDicken and Vergara 1990). Humans have practiced agroforestry for thousands of years, but only since the mid-1970s has an effort been made to collect information on the extent and principles of agroforestry management. Vast areas of land are devoted to agroforestry worldwide. Wood et al. (1984) estimate that as much as 2 billion ha of land are available in the tropical regions for growing tree crops. It likely that agroforestry could be practiced on about a third of this land base (Burley and Stewart 1985).

5) Fuel Woodlot Forestry

In the tropical forest regions, many rural people depend upon wood for cooking fuel, animal fodder, building materials, and other domestic uses (Gregersen et al. 1989). Historically, this wood has been harvested from natural tropical forests. In some locations where the forest resource has been depleted, trees are planted especially for fuel wood. Thus, fuel woodlot forestry is the deliberate cultivation of trees for firewood (Barrett-Lennard et al. 1986). Rotation lengths are often just 5 to 10 years and as many as 60 species of tropical hardwoods have been used (National Academy of Sciences 1980). Fuel woodlots, while sequestering only modest amounts of carbon themselves, can significantly offset deforestation of natural tropical forests, thereby preventing significant losses of existing carbon to the atmosphere. An important research need is to quantify through local case studies how much fuel woodlot forestry actually offsets tropical deforestation (MacDicken and Vergara 1990).

6) Urban Forestry

A significant portion of the world's forests that can contribute to CO_2 mitigation are those maintained within urban and suburban areas. Examples are community parks, greenbelts, roadside forests, and wooded residential and industrial zones. In the United States, the urban/suburban forests total approximately 28 million ha (Grey and Deneke 1978).

5.1.1 Potential for Large-Scale Reforestation to Sequester Atmospheric CO_2

Several researchers have calculated the amount of new forest plantations needed to offset all or part of annual CO_2 emissions and buildup. Dyson (1977) estimated that approximately 700 million ha of new forest would be required to offset the 5 billion tons of total annual global anthropogenic carbon emissions, and that the United States could provide about 10% of this area. Marland (1988, 1989) put the estimate at 500 to 700 million ha depending on the proportions of new plantations in the tropics or temperate zone. Sedjo (1989) concluded that 465 million ha would be required to offset the 2.9 billion ton annual increase (as opposed to total emissions) in atmospheric carbon. Sedjo also cited an unpublished paper by Woodwell (1987) suggesting that 200-400 million ha of additional forest would be required to sequester 1-2 billion tons of carbon annually.

5.1.1.1 Potential rates of carbon sequestration in the tropics: Preliminary analysis

A different approach for evaluating the potential for sequestering carbon through reforestation or afforestation/revegetation is presented in this section. Estimates of land availability and productivity in the tropics are used to calculate the amount of carbon that could be sequestered each year. The focus here is on the tropics because estimates of tropical land availability have been published, and the potential rates of sequestration are higher than most temperate locations (Odum 1983, Waring and Schlesinger 1985).

The term "afforestation/revegetation" is used to indicate a range of options for increasing the productivity of desertified land. This could be achieved by reestablishment of the pre-desertification vegetation cover on a site (i.e. desert scrub, shrubland, or woodland), which is called revegetation here. Or, establishment of plantations of drought-tolerant tree species, here termed afforestation, could be used to increase productivity. In the following analysis, productivity values for natural arid land communities are used (e.g., desert scrub). Determining how to reestablish vegetation or afforest desertified regions is an important research need.

Land availability in the tropics is taken from Wood et al. (1984, Table 5.1-1). Low and high estimates of productivity for tropical regions are used to indicate the range of potential sequestration rates (Table 5.1-2). The method used to calculate sequestration rates is shown in Table 5.1-2.

Results of the analysis show an order of magnitude difference in the range of carbon sequestration rates. Both reforestation and afforestation/revegetation have similar ranges. At the high end of the range, sequestration rates approach over half of the rate of fossil fuel estimates. However, the high end is probably unattainable, because each hectare of land would have to sequester carbon at the highest rate listed in Table 5.1-2. Differences in site condition within a region would prevent this from occurring. It should also be emphasized that the land availability values are highly uncertain because there is no standard approach for estimating available land on a global or continental scale.

Table 5.1-1.   Tropical Lands with Potential for Reforestation   (million ha)   (Wood et al. 1984)

Region	Logged Forests[1]	Forest Fallow[2]	Deforested Watersheds[3]	Desertified Arid Lands[4]	All Lands
Latin America	53.5	65.7	27.5	701.8	848.5
Africa	42.8	58.7	3.0	685.0	789.6
Asia	59.8	56.6	56.5	170.0	342.9
Total	156.2	181.0	87.0	1556.8	1981.0

[1] Almost 90% of these are tropical moist forests (tropical rain forest and tropical moist dec... us forest)
[2] All are in tropical moist forest areas (tropical rain forest and tropical moist deciduous forest)
[3] Montane forest. The area of deforested watersheds is only a rough estimate. It has been included in 'All Lands'.
[4] Savanna and arid lands

Table 5.1-2. Range of Estimates of Carbon Sequestration for Tropical Forests under Scenario of Reforestation or Afforestation.

Region	Available Land[1] (million ha)	Range of Productivity[2] t C/ha/yr	Range of Total C Accumulated[3] (Gt C/yr)
Reforestation:			
Latin America	146.6	1.95 - 10.0	0.29 - 1.47
Africa	104.5	1.95 - 10.0	0.20 - 1.05
Asia	172.9	1.95 - 10.0	0.34 - 1.73
Total	424.0		0.83 - 4.25
Afforestation/Revegetation:			
Latin America	701.8	0.35 - 3.0	0.25 - 2.11
Africa	685.0	0.35 - 3.0	0.24 - 2.06
Asia	170.0	0.35 - 3.0	0.06 - 0.51
Total	1556.8		0.55 - 4.68

[1] Available land estimates are taken from Table 5.1-1; land available for reforestation is the sum of Columns 1,2, and 3 (logged, forest fallow, and deforested watersheds); land available for afforestation is desertified and arid lands.

[2] Low estimate of productivity for reforestation was derived from the estimated minimum total biomass accumulation over 40 years in tropical plantations from Brown et al.(1986). (155.7 t/ha w 40 yrs x 0.5 [carbon-to-biomass conversion factor] = 1.95 tC/ha/yr.
High estimate of productivity was derived from an estimate of gross primary production for wet tropical forests (Odum 1983) (2000 kCal gross primary production/m^2/yr = 1 t C net primary production/ha/hr; assuming 10 kCal equals 1 g C and net primary production equals half of gross primary production).

Range of productivity for afforestation is from estimated net primary productivities by ecosystems (Waring and Schlesinger 1985). The "desert scrub" ecosystem is used for the low estimate and "woodland and shrubland" ecosystem for the high estimate.

[3] Low and high estimates of total carbon accumulated are the product of land area and low and high productivity, respectively.

5.1.1.2 Reforestation workshop

A recent workshop on international reforestation was sponsored by the EPA at ERL-C. The workshop explored ecological, operational, and sociopolitical considerations for successful large-scale reforestation projects. Workshop participants included about 50 forest managers and scientists from Brazil, British Columbia, Congo, Guatemala, India, New Zealand, the United Kingdom, and United States Pacific Northwest and Southeast regions. The workshop was designed to gather knowledge from these participants to guide decision makers in implementing future large-scale reforestation projects. A list of participants is given in Appendix C.

Participants agreed on two important points:

1)   Current technical and ecological knowledge, though needing research in a few key areas, is adequate to undertake large-scale projects for some initial increases in reforestation on a global scale (Smith 1986, OTA 1984).

2)   Of all the requirements needed for successful reforestation, the social and political limitations, especially in the developing nations, were emphasized repeatedly. These limitations take many forms, but most important are: a) the differential awareness many people have of the value of forests; b) the need for financial incentives or alternative incomes, particularly to encourage small landowners or migrant people at subsistence living standards to plant and grow trees; and c) the lack of governmental infrastructure in many nations to undertake large-scale reforestation projects (Gregersen et al. 1989). .

Participants also used their combined knowledge to estimate carbon sequestration rates for various forest systems (Table 5.1-2).

3). For the tropics, the rates estimated in Table 5.1-3 are at the high end (Brazil and Congo) of published values in Table 5.1-2. The greatest uncertainty in Table 5.1-3 is whether these high rates could be implemented over millions of hectares.

To place the amount of effort needed to reforest the land listed in Table 5.1-1 in context, consider that during the 1980s, about 16.4 million ha in the world were planted to trees annually (Table 5.1-4). Most forestation occurred in temperate latitudes. To plant 750 million to 1 billion ha of land in the world over 25 years (a period accepted as reasonable at the above workshop), an annual rate of 30 to 40 million ha

is required. Socioeconomic barriers must be overcome before significant forestation will occur in tropical latitudes. Establishment of sustainable agroforestry systems with multiple purpose trees offers one attractive alternative (Jain et al. 1989).

Another factor affecting the feasibility of reforestation as a management option is cost. Experts at the workshop estimated establishment costs ranging from $200 to $1700/ha depending upon the species and geographic location. Comprehensive economic analyses are needed to evaluate the cost of forest planting. Evaluation of the societal and environmental impacts of reforestation and afforestation are also required.

Table 5.1-3.   Examples of Potential Wood Volume Growth and Calculated Carbon Fixation Rates, and Representative Establishment Costs for Several Species in the Tropical and Temperate Zones. Based on Opinions of Individual Reforestation Experts at an International Workshop (Winjum and Schroeder *in preparation*)

Species	Wood Volume m^3/ha/yr	Carbon [1] tC/ha/yr	Establishment Cost ($/ha)
Tropics:			
Tropical hardwoods (Brazil)	35	15	800
Eucalyptus spp. (Congo)	25	10	1400
Casuarina spp. (India)	9	4	200
Temperate:			
Pinus radiata (New Zealand)	25	10	300
Picea sitchensis (UK)	14	6	1100
Pinus taeda (US)	9	4	300
Pseudotsuga menziesii (US)	14	6	1700
Pseudotsuga menziesii (Canada)	6	2.5	1000

1 Carbon sequestration rates are developed by multiplying wood volume by 1.6 to get total biomass volume/ha/yr and by 0.26 to get t C/ha/yr (Sedjo and Solomon 1989). These rates are just for the first rotation of the plantations and do not account for carbon lost by harvesting and growing plantations in perpetuity.   ·

Table 5.1-4.   Global Reforestation/Afforestation   Rates in the 1980s

Region/Area	Area ha/yr x 1000	Reference
Boreal:		
Canada	112[2]	Scarratt et al. 1982
Scandinavia	620[2]	Scarratt et al. 1982
USSR	550[2]	Postel and Heise 1988
Temperate:		
Argentina	55	Postel and Heise 1988
China	7,000[2]	Lonqjun circa 1986
India	5,000[2]	Sharma et al. 1989
Japan	240	Postel and Heise 1988
South Africa	110	Postel and Heise 1988
United States	1,200	Foreward et al. 1990
Western Europe[1]	475	Postel and Heise 1988
Tropical:		
Africa	127	Postel and Heise 1988
Asia	439	Postel and Heise 1988
Latin America	534	Postel and Heise 1988
Total	16,462	

[1]   Estimate is for 1970s
[2]   Land area estimated by dividing the reported annual numbers of seedlings planted by 1,200 seedlings/ha.

5.1.2 Calculation of the Carbon Sequestering Potential of Temperate Plantations: An Example

The following sections report the results of a study conducted at ERL-C (Schroeder and Ladd *in press*), the goal of which was to calculate the area of forests that would have to be planted in the United States to store the total anthropogenic carbon emissions of the United States over a 50-year period.

5.1.2.1 Approach

The United States emits about 1 billion tons of carbon per year, which comes to 50 billion tons over a 50-year period if we also assume that emission rates do not change (Manne and Richels *in press [a,b]*). Fifty years is an arbitrary assumption. What is important here is the approach used to calculate the area of plantations that would be required, given a 50-year time period. Furthermore, the analysis only accounted for the amount of carbon that could be stored during the 50-year period and did not consider its fate at the end of that time. Also, the analysis did not consider potential climate change effects on forests. As discussed in Section 3.2, vegetation redistribution could create a significant pulse of carbon to the atmosphere, further increasing atmospheric CO_2 concentration and making reforestation efforts more complicated and potentially less effective. Decomposition has already been accounted for in the following estimates.

The forestation/mitigation analysis considered two tree species important in the South and Northwest, respectively: loblolly pine and Douglas-fir (Barrett 1980). Calculations of stand growth and carbon fixation rates were based on output from standard forestry growth and yield models. These are empirical models commonly used to predict the volume growth of stemwood that can be converted into usable products. For loblolly pine, the analysis used the model PTAEDA2 (Burkhart et al. 1987), and for Douglas-fir the model DFSIM (Curtis et al. 1982) was used. Because they are empirical models, PTAEDA2 and DFSIM assume that future stand development will be similar to past stand development (i.e., similar to the data on which the models are based). They therefore cannot account for the potentially complex influence of a changing climate.

As Sedjo (1989) assumed, 1 m^3 of stemwood was associated with 1.6 $m4^3$ of whole-tree biomass (roots, branches, leaves, etc.). The analysis also followed both Marland's (1988) and Sedjo's (1989) analyses by assuming that 1 m^3 of biomass contains 0.26 tons of carbon (tC). As with previous studies, the present one did not account for carbon storage in forest floor detritus or soil, nor was the potential impact of atmospheric CO_2 enrichment itself considered.

5.1.2.2 Results

The carbon fixation rate for loblolly pine was 4.0 tC/ha/yr (Figure 5.1-1), or a total carbon storage capacity of 200 tons C/ha over 50 years. For Douglas-fir the annual fixation rate was 5.2 tons C/ha/yr (Figure 5.1-1), and storage was 260 tons C/ha for the 50-year period. It would thus take 250 million ha of loblolly pine or 192 million ha of Douglas-fir to capture and store the 50 billion tons of carbon that would be emitted over the 50-year time period. For perspective, consider that 200 million ha is about 26% of the total area of the 48 contiguous United States, and the total worldwide area of commercial forest plantations in the mid-1980s was about 92 million ha (Postel and Heise 1988).

The reason that 30% more area is required to store the same amount of carbon with loblolly pine than with Douglas-fir over a 50-year period is illustrated in part by Figure 5.1-2 and is explained by Figure 5.1-1. Although the two species may have similar rates of carbon fixation at certain points in their life cycle, Douglas-fir is structurally capable of higher levels of carbon storage. The point of maximum growth for loblolly pine occurs relatively early, before much carbon has accumulated (e.g., 20-30 yrs). Indeed, throughout much of the assumed 50-year period, mean annual increment (MAI) for loblolly pine actually declined, and total yield or carbon storage was nearly constant. The pine stand essentially reached its maximum carbon storage capacity at approximately age 30. For the next 20 years little additional carbon was accumulated. Over a period greater than 50 years, therefore, the disparity in land requirements for the two species would be even greater. Continuing high rates of fixation while maintaining carbon in storage may be difficult with loblolly pine.
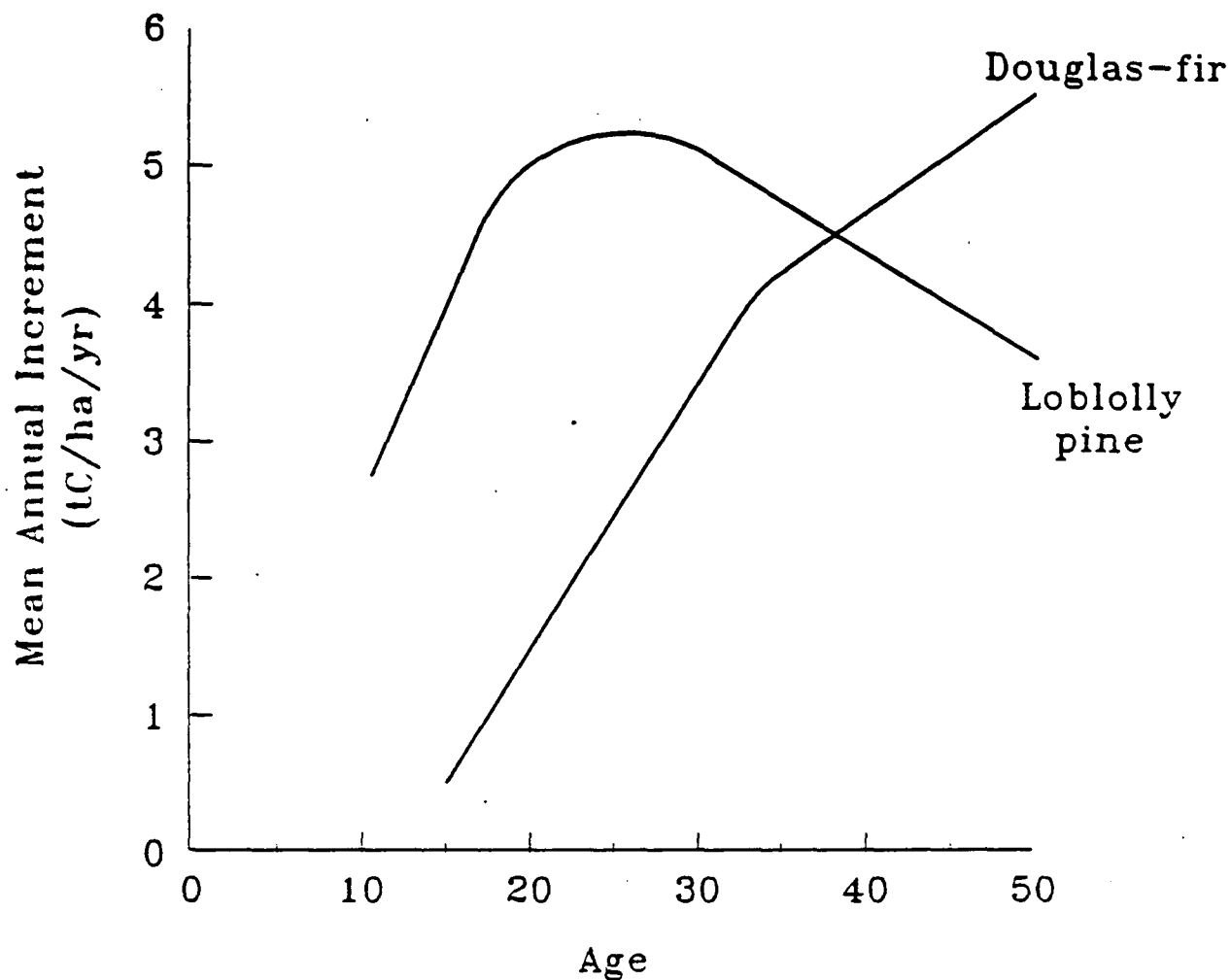
Figure 5.1-1.   Comparison of changes in estimated mean annual growth increment of Douglas-fir and loblolly pine. Estimates assume Douglas-fir site index 125 (base age 50 yrs) and initial planting density of 1000 trees/ha, loblolly pine site index 70 (base age 25 yrs), and initial planting density of 1500 trees/ha. (Site index is a forestry productivity classification concept. It is simply the mean height of the dominant (tallest) trees at some particular age. The concept is based on the understanding that height growth is very heavily influenced by, and therefore integrates the effects of, the physical and environmental factors that determine site quality.)
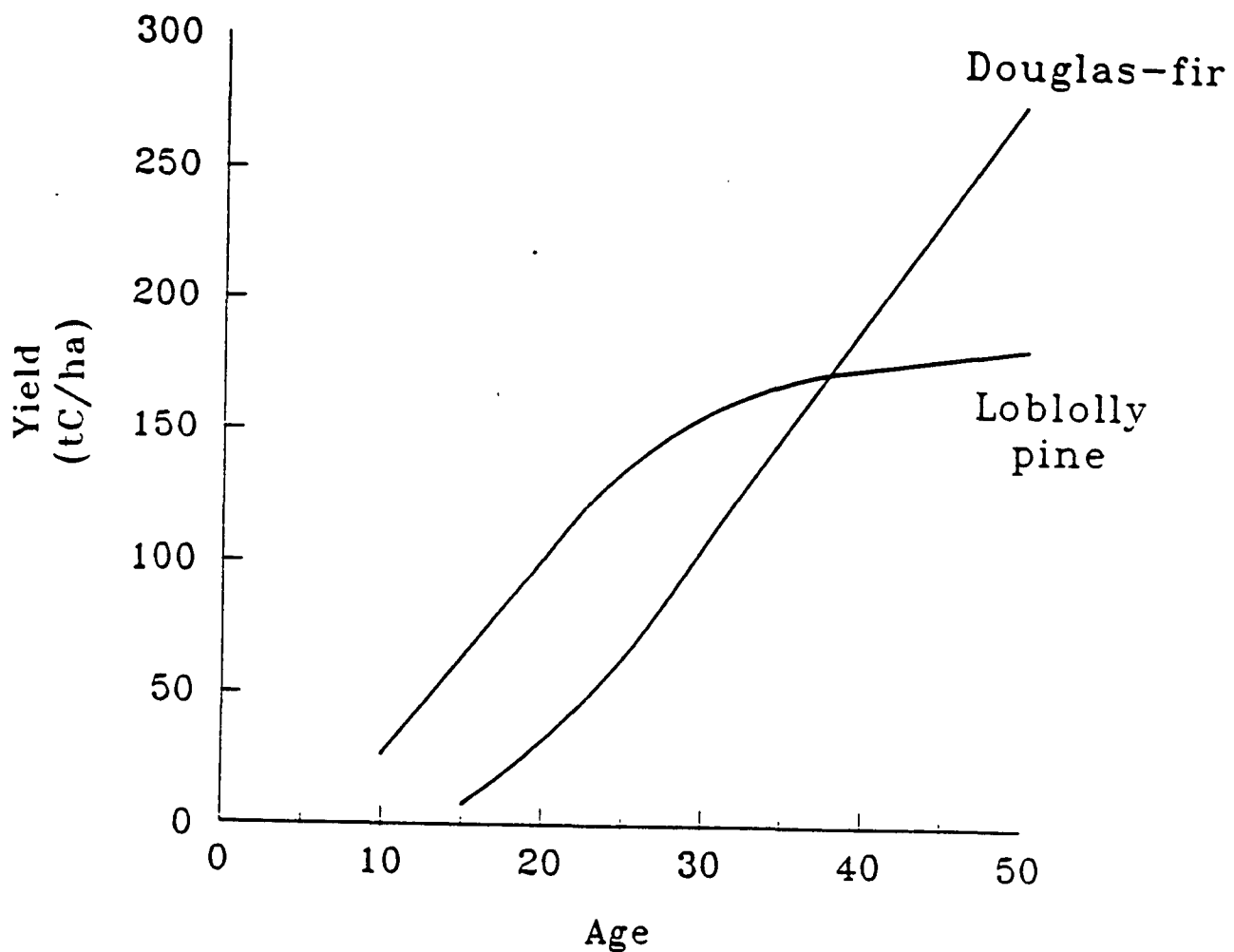
Figure 5.1-2.   Estimated yield curves of total standing crop for Douglas-fir and loblolly pine based on the same assumptions as Figure 5.1-1. Lower early yield for Douglas-fir (i.e., 7.5 tons C/ha at age 15) reflects the lower juvenile growth rate illustrated in Figure 5.1-1.

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One possible solution is to grow two 25-year crops of a species like loblolly pine during the 50-year period, harvest trees at age 25 when they have achieved nearly maximum storage, and replace them with a vigorous young stand. For this approach to be successful, the harvested carbon must not find its way back into the atmosphere (or must be used to replace fossil fuel). Unfortunately, the amount of carbon that can actually be stored in the form of durable products (e.g., lumber or plywood) is fairly small. Harmon et al. (1990) estimated that only about 42% of harvested stemwood carbon goes into durable products. The remainder is lost to paper production, fuel consumption, and decomposition. (Unaccounted for, however, is carbon in an unknown amount of paper that can lie buried but undecomposed in landfills for several decades.) This analysis accounted for branches, leaves, and roots in addition to stems. Since these components comprise about 40% of total carbon and since none of them go into durable products, only about 25% of the total carbon accumulation estimated here could be converted to durable products. This illustrates the transitory nature of carbon storage in forests.

It was calculated that total yield for a 25-year crop of loblolly pine would be 133 tC/ha (Figure 5.1-2). Because 75% of this amount returns to the atmosphere, however, only about 33 tC/ha would go into long-term storage. This 33 tons combined with an additional 133 tons from a second 25-year crop (unharvested) would succeed in storing 166 tC/ha over a 50-year period. This is 17% less than a single 50-year crop.

5.1.2.3 Conclusions

This analysis demonstrates the significant influence of forest growth patterns over time on achieving carbon storage goals. If the policy objective is to slow the increase in atmospheric CO_2 concentrations, then the emphasis should be on carbon storage over several decades. Concentration on short-term average annual rates of carbon fixation without consideration of the growth dynamics of forest stands over time can be misleading. For periods of 50 or more years, it is especially important to be mindful of a species' carbon storage potential rather than of its potential maximum growth rate at some point during its life cycle.

The analysis also shows that large areas of land are required to offset the CO_2 emissions of a developed economy like that of the United States. Forestation alone may not solve the problem of increasing atmospheric CO_2 concentration, but it can result in the storage of large amounts of carbon. However, establishment of new forests can be a valuable component in a comprehensive solution that also includes reductions in CO_2 emissions from fossil fuel combustion and deforestation. It is unlikely that the developed countries, the largest sources of anthropogenic CO_2, have sufficient land available to

offset even their own CO_2 emissions through forestation (Shands and Hoffman 1987). Consequently, any strategy including forestation as a component must be implemented globally.

5.1.3 Calculation of the Carbon Sequestering Potential of Several Forest Stand Treatment Practices

This section analyzes the effects of thinning, fertilization, and vegetation control on carbon storage based on output from temperate forest growth and yield models, and values derived from the literature. The species, models, and methods used were the same as those described in the previous section. Different assumptions, models, etc., are probably applicable to boreal and tropical species (Burley and Stewart 1985).

5.1.3.1 Thinning

Thinning of forest stands is a common management practice despite the fact that, paradoxically, it may actually reduce total yield (in terms of timber or carbon) over the length of a rotation (Smith 1986). Simulated examples of this for Douglas-fir and loblolly pine are shown in Table 5.1-5.

Table 5.1-5. The Effect of Stand Thinning on Carbon Sequestration

Species	Unthinned tC/ha	Thinned tC/ha	%Reduction	Including Thinnings tC/ha	%Reduction
Douglas-fir[1]	260	210	19	240	8
Loblolly Pine[2]	170	145	15	151	11

[1] Simulation assumptions: Reasonably good quality site (site index 125 at age 50), planted at 750 trees/ha, 50 yr rotation thinned once at age 35.

[2] Simulation assumptions: Reasonably good quality site (site index 70 at age 25), planted at 1500 trees/ha, 35 yr rotation thinned once at age 25.

By redistributing stand growth to a smaller number of larger trees, thinning can be used to increase the value of merchantable stemwood volume even if total production of wood, or storage of carbon, is unaltered or even somewhat reduced. In his classic silviculture text, Smith (1986) explains that for a given age, composition, and site, total stand volume production is essentially constant for a wide range

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of stocking density. It can be decreased, but not increased, by altering the amount of growing stock to levels outside of this range. Farnum et al. (1983) allowed that small increases in productivity may result from early thinnings of dense stands that leave only well-spaced stems on the best microsites, but they also concluded that overall productivity is not changed substantially by thinning.

5.1.3.2 Nutrient fertilization

The objective of nutrient fertilization is to increase tree growth by supplying the nutrient elements that are limiting growth (Pritchett and Fisher 1987). A comprehensive review of literature on forest fertilization is beyond the scope of this report (Dangerfield and Brix 1981). Rather, this section will demonstrate some concepts and principles regarding the effectiveness of fertilization in enhancing carbon storage in forests (Shands and Hoffman 1987). The results cited below were reported in the literature in terms of growth or volume responses to fertilization, and they have been converted to estimates of carbon storage for this report.

General estimates of fertilizer response

Douglas-fir generally responds positively to nitrogen fertilization. However, the magnitude of the response can vary greatly, which makes it difficult to predict quantitatively as a function of soils (Ballard and Shumway 1986). The estimates that follow should therefore be considered as general and subject to fairly wide variation. Farnum et al. (1983) estimated that repeated periodic application of nitrogen fertilizer would increase the maximum mean annual growth increment of Douglas-fir by 20% over a rotation. Miller et al. (1986) reported results from an extensive set of nitrogen fertilization trials for Douglas-fir. They observed increases in basal area growth (roughly comparable to volume growth and, therefore, to carbon fixation rate) of about 20% over a six-year period for a variety of application rates, site conditions, and stand conditions in the Pacific Northwest. Peterson and Gessel (1982) reported that the fertilized stands in the same study were outgrowing controls by about 18% or 1.5 tC/ha/yr after eight years.

The response of loblolly pine to fertilization is also variable. Farnum et al. (1983) estimated increases in mean annual volume growth of loblolly pine of 20% as a result of phosphorus fertilization. They estimated an increase of an additional 12% for nitrogen fertilization. Comerford et al. (1982) reported that phosphorus fertilization increased the annual growth of a young pine stand by about 64% or just over 3 tC/ha/yr. Ballard (1981) concluded that nitrogen fertilization can produce a volume increase on a wide variety of sites used for loblolly pine plantations. He reported gains of 1-2 tC/ha/yr over a period

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of five years following nitrogen application. Ballard et al. (1981) reported increases of about 1 tC/ha/yr for the four-year period following nitrogen fertilization for 12 loblolly pine plantations.

Fertilizer interactions

Fertilization can interact with site quality, stand density, and age. Figure 5.1-3 is derived from data contained in Miller et al. (1986), and it shows a typical inverse relationship between site quality and nitrogen fertilizer response. Lower quality sites generally respond more positively to fertilizer application than better quality sites, both in relative and absolute terms. Indeed, over the 10-year period presented, the fertilizer response of the lowest quality sites was about fourfold that of the highest quality sites. The same general relationship was also observed by Peterson and Gessel (1982).
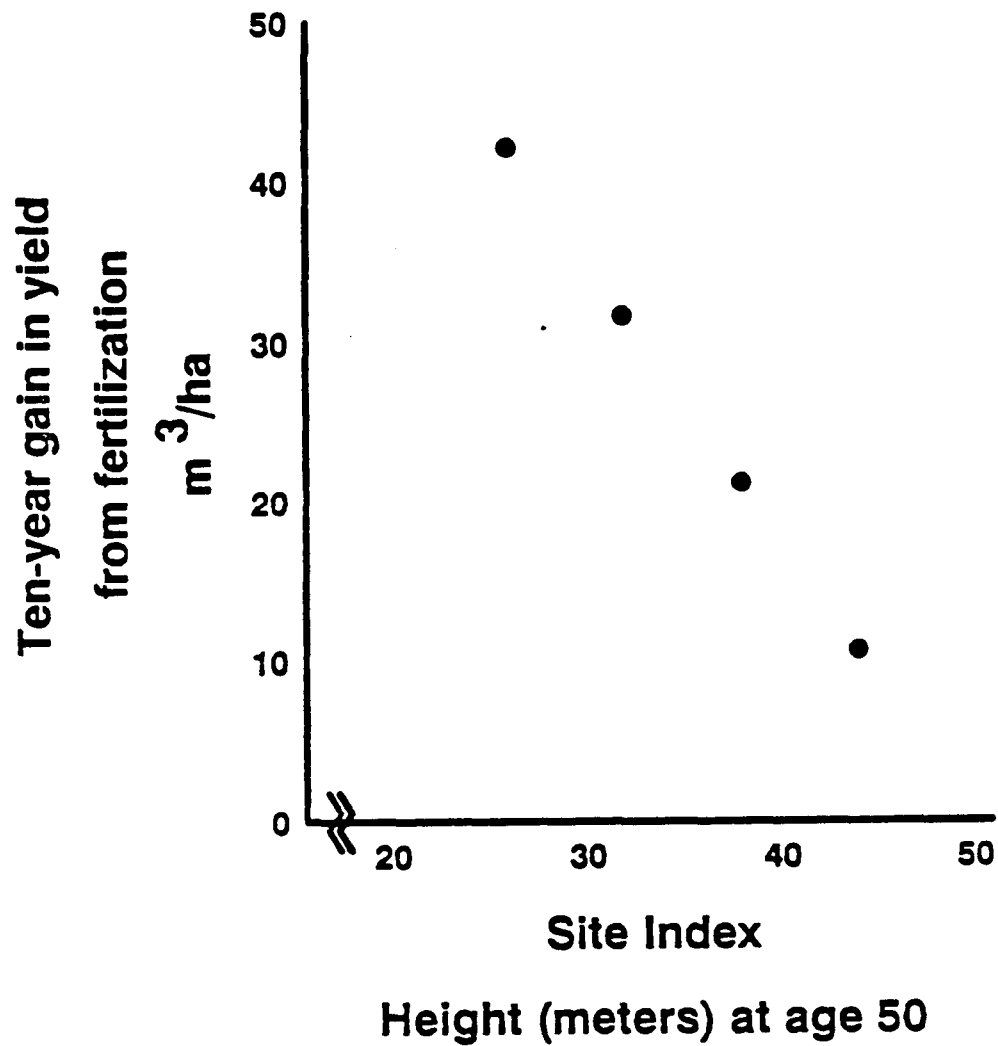
Figure 5.1-3.   Cumulative 10-year increases in Douglas-fir stem biomass (carbon gain) resulting from fertilization with 224 kgN/ha (from Miller et al. 1986).

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Regarding interactions with stand density, Peterson (cited in Miller et al. 1986 and *personal communication*) has pointed out that by increasing stand growth, and therefore increasing competition for space and other resources, fertilization may increase mortality in unthinned stands. When thinned stands are fertilized, all or most of the growth increase stays in the living forest, and is not returned to the atmosphere via decomposition and respiration. Although thinning by itself does not increase total carbon storage, fertilizing stands that have already been thinned, or that are soon going to be thinned, appears to offer a good opportunity for gains in carbon storage. Douglas-fir and loblolly pine have both been shown to respond positively to fertilization over a wide range of age. Positive fertilizer response for Douglas-fir has been observed in stands from 9 to 120 years of age (Miller and Webster 1979, Miller et al. 1986, Peterson and Gessel 1982). Loblolly pine is not as long-lived as Douglas-fir, but Ballard's (1981) data referenced above include stands that are 4 to 21 years old.

Carbon cost of fertilizer production

The production of commercial fertilizers must also be considered with respect to carbon storage. Ammonia, the base component for the nitrogen fertilizer industry, is produced from atmospheric nitrogen and hydrogen from natural gas or petroleum. Carbon dioxide is produced as a byproduct when the carbon atom is stripped from the natural gas hydrocarbon to leave the hydrogen atoms. Approximately 4 tons of CO_2 are produced for every ton of ammonia manufactured (Sittig 1979). These reactions are also carried out at high temperature and pressure, which requires energy inputs and subsequent additional CO_2 release. A common nitrogen (N) fertilization application rate is about 250 kgN/ha, or 0.25 tons N. Manufacturing this amount of fertilizer would, therefore, entail the production of at least a ton of CO_2 containing 270 kg carbon. This means that the net carbon storage would be reduced by 2-5% over a period of 5-8 years, based on data presented above. Other CO_2 costs of forest management, primarily from energy usage, should also be noted.

Effects of fertilization on other ecosystem properties

Besides increasing the rate of plant growth, additions of nutrients may affect a number of other processes in ecosystems. Some examples of these processes include decomposition rates (Melillo et al. 1982), rates of grazing activity (Mattson and Addy 1975), competitive abilities of plants (Ruess et al. 1983), carbon allocation to roots (Hermann 1977), or even soil chemical properties (Ruess and Johnson 1986). These effects in turn may act to further increase the potential to sequester carbon if added in moderate amounts, but they also could reduce carbon sequestration if added in excess. An example of

excess amounts of nutrient inputs is the chronic deposition of acidic compounds into certain sensitive forests (Schulze 1989, Materna 1989).

5.1.3.3 Control of competing vegetation

The control of competing vegetation in young plantations is another common practice (Gjerstad et al. 1984) important for enhancing carbon storage capability. A few examples for loblolly pine simulated with the PTAEDA2 model illustrate the relative sizes of potential effects of competition on growth carbon storage. A low level of competition (5% of the total stand stocking) would result in a 13% growth loss or about 23 tC/ha over a 35-year rotation. If this competition were eliminated at an early age, such as within the first five to eight years, there would be no growth loss. A high level of competition (15% of stand stocking) would result in a 35% growth loss over 35 years, which is equivalent to nearly 60 tC/ha. Controlling this level of competition early in stand development would prevent nearly all of the growth loss. However, if controlling this level of competition is delayed, until age 20 for example, final carbon storage would be reduced by about 31 tC/ha or 18%.

5.1.3.4 Discussion and conclusions

Reforestation or afforestation of lands currently denuded of trees will ultimately result in larger amounts of carbon storage than can be attained by intensifying management of existing forests. Some of the growth data presented here, in the previous section, and elsewhere (Schroeder and Ladd *in press*) show potential carbon accumulation rates of 4-6 tC/ha/yr for reforested areas, as compared with the 1-2 tC/ha/yr increase in carbon accumulation for other forest management practices. On a unit area basis, this increase is still notable. On a global basis, however, the impact of intensified forest management on atmospheric CO_2 will depend on the area of forest that can be successfully utilized.

This discussion of forestry practices and the dynamics of forest growth and development leads to several conclusions about carbon storage in temperate Douglas-fir and loblolly pine forests:

1)   Thinning does not generally increase carbon storage, although thinning dense young stands may increase carbon storage over the life of the stand (Section 5.1.3.1).

2)   Fertilization generally increases carbon storage, although the actual level of response can be difficult to predict (Section 5.1.3.2).

3)   Fertilization may result in greater carbon storage on low-quality sites than on high-quality sites (Section 5.1.3.2).

4)   Forest stands over a wide range of ages respond positively to fertilization, which may offer opportunities for increasing carbon storage (Section 5.1.3.2).

5)   Fertilizing unthinned or dense stands increases net carbon storage, but fertilizing thinned or less dense stands results in an even greater net removal of carbon from the atmosphere (Section 5.1.3.2).

6)   Control of competing vegetation maximizes carbon storage in trees over the life of a stand (Section 5.1.3.3).

5.1.4 Research Needs

The analyses discussed above in Sections 5.1.1 to 5.1.3 suggest that forest management, particularly reforestation/afforestation, can play a role in reducing the rate of increase of atmospheric CO_2 These analyses, however, are admittedly preliminary. Uncertainties in the estimates presented here can be reduced by completing the following research tasks:

1)   Inventory and classify land areas that are suitable and available for reforestation/afforestation.

2)   Determine rates of carbon fixation and storage for other tree species, particularly tropical species.

3)   Estimate the carbon storage potential of agroforestry systems, including carbon accumulated as soil organic matter.

4)   Determine the effectiveness of agroforestry to reduce rates of deforestation by reducing the area of land required to meet agricultural and wood needs.

5)   Develop methods to reforest land that has been degraded by overuse or misuse.

5.2 Soil Management to Conserve and Sequester Carbon

Soil carbon in tropical, temperate, and boreal forests accounts for 40% of the 1500 Gt of carbon estimated to be in world soils (Waring and Schlesinger 1985). Land use practices such as harvesting and permanent clearing can affect these soils and can lead to emissions of carbon to the atmosphere (Jain et al. 1989). Evaluation of strategies to manage and use world forests to sequester and store carbon should consider the role that soils play in carbon storage as well as their role in reforestation and afforestation (Dixon *in press,c*).

Recently, at a workshop held by EPA at ERL-C, policy and science experts on agricultural and forest soils considered the potential role of soils in mitigating increases in atmospheric CO_2 (see Appendix B for list of attendees). The principal workshop question was, "Can soils be used to store sufficient carbon to aid in mitigating the extent of global climate change?" The participants concluded that data are currently insufficient to answer this question definitively.

There was, however, a general consensus that three strategies could promote carbon storage in soils. The first is to implement soil management techniques that maintain current pools of soil carbon and that minimize the loss of carbon from soils to the atmosphere (as either CO_2 or methane), such as minimizing soil disturbance during forest harvesting (Parton et al. 1988, Miller and Sirois 1986, Mattson and Swank 1989). The second approach is to implement management practices that would restore soil carbon in carbon-depleted soils (Oades 1988, Pritchett and Fisher 1987); for example, reforesting marginal lands that were once cleared for agriculture. The third strategy is to promote management techniques to enlarge the size of the existing soil carbon pool. For instance, soil carbon sequestering could be enhanced by retaining slash on site instead of removing it by burning (Benson 1982, Jain et al. 1989, Yonker et al. 1988). Workshop participants produced a list of specific management tools for both agricultural and forested systems that could be implemented under each of these three approaches, and ranked their relative priority. These tools are shown in Table 5.2-1 and a subset is discussed in some detail below.

5.2.1 Maintaining the Soil Carbon Pool

As described in Section 2.3, the carbon content of soils is a function of a variety of factors including past and present management. Historically, forest soils have not been managed to conserve carbon (Pritchett and Fisher 1987). In fact, some forest management practices are purposefully designed to remove slash and detrital carbon to facilitate or expedite replanting. Other practices such as the

conversion of forested lands to agriculture can lead to the net loss of soil carbon (Giddens 1957, Delcourt and Harris 1980, Allen 1985, Schlesinger et al. 1990). In all likelihood, such land use changes will mean loss of soil carbon to the atmosphere.

The world demand for forest products is not likely to decline in the immediate future, so forests will continue to be a source of raw materials (USDA 1988). Changing the way forest soils are currently managed, however, can minimize the loss of soil carbon and promote longer term sustainability of these systems. Five potential approaches are: 1) maintaining forest soil fertility; 2) retaining forest slash and residues on site; 3) using prescribed burning to maximize carbon storage; 4) minimizing site disturbance; and 5) controlling erosion.

Table 5.2-1. Prioritized Strategies for Sequestering and Storing Carbon in Soils [1]

| | Approach[2] | | |
Management Practice	Maintain	Restore	Enlarge
Minimum Tillage	M[3]		H
Reforestation		H	
Maintain or Improve Soil Fertility	H	H	H
Retain Forest Slash on Site	M		M
Leave Crop Residues	M		M
Incorporate Crop Residues	L		M
Intensify Tropical Agriculture	H	M	H
Increase Efficiency of Forest Product Use	H		
Minimize Site Disturbance	M		
Use Prescribed Burning to Maximize Carbon Storage	M		
Take Marginal Lands out of Intensive Agricultural Production		M	M
Control Erosion	M	M	L
Preserve Natural Wetlands	H		
Use Municipal, Animal, Industrial and Food Processing Wastes		H	M
Urban Forestry		L	
Minimize Dryland Fallowing			H
Use Mulching	M		M

[1] Recommendations/suggestions made by general consensus of scientific panel at ERL-C Workshop, February 1990. List of participants is given in Appendix B.

[2] Maintain, Restore, and Enlarge are defined in the text (Sections 5.2.1, 5.2.2, 5.2.3)

[3] Priority: H, high; M, moderate; L, low.

5.2.1.1 Maintaining forest soil fertility

The principal objective of this management strategy is to keep the land in production (Barrett-Lennard et al. 1986). Maintaining soil fertility simply means the implementation of management practices that prevent the degradation or loss of the capacity of the soil to supply nutrients. Practices such as interplanting with nitrogen-fixing plants (Binkley et al. 1982) may lead to more fertile systems and in all likelihood more productive systems on a sustained basis (Burley and Stewart 1985).

5.2.1.2 Retaining forest slash and residues on site

Forest harvest residues are an important source of organic matter and nutrients for the next rotation as well as an important substrate for heterotrophic organisms (Swift 1977, Harmon et al. 1986, Pritchett and Fisher 1987). Quite often these residues are either removed or burned following forest harvesting. Burning and heterotrophic decomposition of these materials both result in the emission of CO_2 Burning also results in the loss of nitrogen to the atmosphere and may damage the soil and the soil biology (Office of Technology Assessment [OTA] 1984). Burning may also leave the soil bare, making it more susceptible to erosion, particularly in humid regions on steep slopes. If the organic matter is retained on site and incorporated into the soil, net carbon emissions to the atmosphere could be reduced (Yonker et al. 1988) and site productivity increased (Jain et al. 1989).

5.2.1.3 Using prescribed burning to maximize carbon storage

Prescribed burning has been used for centuries as an effective method for removing slash following a forest harvest or in shifting to agriculture. Changing the way slash is burned may, in some situations, increase rather than decrease, the potential for a site to sequester and store carbon (Pritchett and Fisher 1987). Very hot burns (i.e., hot dry and windy weather and dry slash) may severely damage the soil. Such burns can be so hot that they combust organic matter in the forest floor and soil, destroying seed beds, still-living root systems, mycorrhizae, and free-living soil organisms (Waring and Schlesinger 1985, Perry et al. 1989).

5.2.1.4 Minimizing site disturbance

Some logging systems during forest harvesting may compact or disrupt a large portion of the soil in the harvest areas (Miller and Sirois 1986 Smith 1986). This could reduce the productivity of the site and

promote the loss of soil carbon. Harvest and management practices that minimize or eliminate site disturbance will help maintain the productivity of the forest system (Barrett 1980, Perry et al. 1989).

5.2.1.5 Erosion control

Erosion results in the loss of the soil resource and with it the potential to sequester and store carbon (Parton et al. 1988). The purpose of controlling soil erosion is to maintain the soil resource, the productivity of the system, and the potential for carbon to be stored belowground.

5.2.2 Restoring Soil Carbon

Worldwide, millions of hectares of once-forested land may be denuded of vegetation (Grainger 1988). Accompanying the loss of vegetative cover is the loss of soil carbon (Schlesinger et al. 1990). Management practices that restore these lands into production will lead to increased carbon sequestration and storage both above- and belowground (Dixon *in press,c*).

Strategies for restoring soil carbon in forested (or once forested) systems include: 1) reforestation (Wiersum 1984); 2) intensifying tropical agriculture (MacDicken and Vergara 1990); 3) improving soil fertility (Pritchett and Fisher 1987); 4) removing marginal lands from intensive agricultural production (Barrett-Lennard et al. 1986); and 5) urban forestry (Grey and Deneke 1978).

5.2.3 Enlarging the Soil Carbon Pool

Increasing the productivity of ecosystems by enhancing or enlarging the size of the soil carbon pool is a third strategy for storing more carbon belowground (Dixon *in press,c*). Most of the opportunities to enlarge this pool may be in agriculture because agricultural systems are generally more intensively managed than forested systems (Smit et al. 1988). Of the three strategies for storing carbon in soils, this approach has the lowest priority. Preliminary consideration suggests that the marginal return, measured in stored carbon, would be greater if the first two strategies are implemented. However, some opportunities exist to enlarge soil carbon pools in forested systems, including improving soil fertility and retaining forest slash on site (Pritchett and Fisher 1987, Shands and Hoffman 1987).

To expand on one of these strategies, the addition of fertilizers to soil may increase soil carbon pools above their normal, steady-state levels. Fertilizers can increase carbon flow in the soils via increasing the rate of carbon fixation into plants and thus also increasing detrital inputs into soils (Attiwill 1986).

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A second and less understood way fertilizers may increase soil carbon pools is by reducing decomposition and CO_2 efflux back to the atmosphere. For example, following nitrogen fertilizer treatments in forests in Sweden, reduced decomposition and reduced soil respiration have been observed (Nohrstedt et al. 1989). Similarly, nitrogen additions have caused a substantial reduction in CO_2 efflux to the atmosphere at a forest site in the Oregon Cascades (Figure 5.2-1). The causes for the reduction are unknown at the present. Hypotheses include altered soil solution chemistry, shifts in microbial population, suppression of lignolytic activity of fungi, and reduced root respiration. The large depression of CO_2 efflux suggests that fertilization is an important factor controlling carbon flow.

5.2.4 Future Considerations

The strategies discussed here are aimed at storing carbon in soils of forest ecosystems. The approaches appear to be applicable to both temperate and tropical forest systems (Jain et al. 1990, Pritchett and Fisher 1987). Uncertainties exist in the implementation of these practices because negative effects associated with a given practice may outweigh the positive benefits at particular sites. Under certain circumstances, for instance, some of the recommended carbon sequestering techniques could lead to the emission of gases that are more radiatively efficient than CO_2 (e.g., reducing environments caused by intermittent flooding may enhance the efflux of methane and nitrous oxide, while reducing the efflux of CO_2), and therefore, in terms of global warming, would be counterproductive (Tans et al. 1990, Post et al. 1982). The exact nature and extent of the uncertainties cannot be fully evaluated without more research (IPCC 1990). The implementation of these management practices should be considered on a site or regional basis and should be judged in terms of their effect on the carbon pools and fluxes (Dixon *in press,b*).

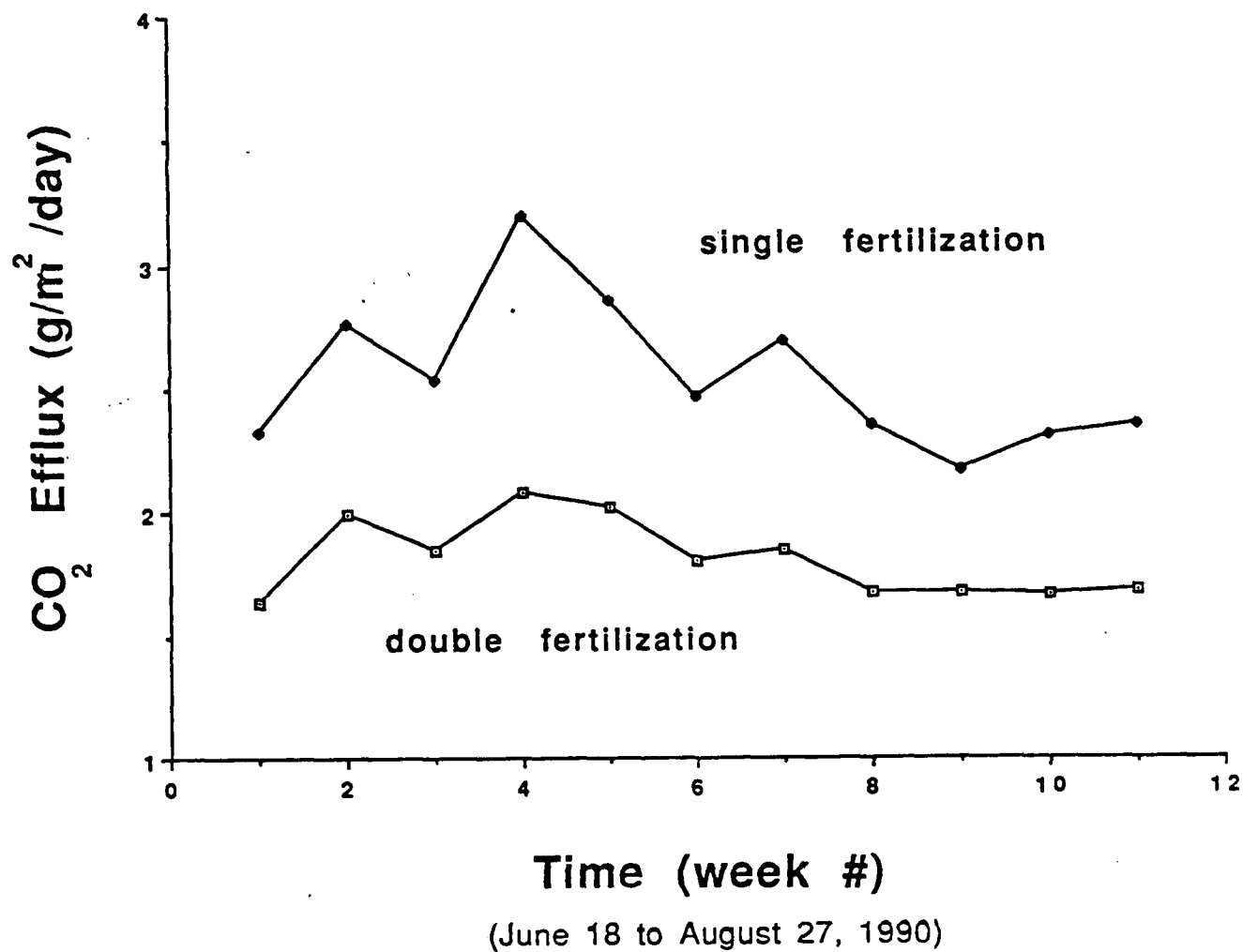Figure 5.2-1.　CO_2 flux from soil and forest floor to the atmosphere at fertilized Douglas-fir and western hemlock forested sites in the Oregon Cascades. Reductions of 35% in CO_2 efflux occur as a result of added nitrogen. Nitrogen additions (urea, 300 kgN/ha) were added several years ago to both sites and again this spring to one site; i.e., the single and double fertilized lines, respectively.

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In addition to storing carbon assimilated from the atmosphere, managing forested soils to conserve carbon has additional benefits, including: 1) increased soil water holding capacity; 2) increased nutrient availability; 3) improved soil physical properties; and 4) decreased soil erosion by wind and water. Costs for implementing various soil carbon conservation practices need to be determined.

5.2.5 Research Needs

The storage of carbon in soils is a complex process that is not fully characterized or understood as yet (Post et al. 1982). To implement biospheric management strategies for mitigating global change, the effects of specific management practices on soil carbon cycling must be more fully understood (IPCC 1990). If the purpose is to capture atmospheric CO_2 for storage in the biosphere, including storage in soils, then the following areas require investigation:

1)   Identification and characterization of the specific pools of soil carbon that can be managed (Post et al. 1982).

2)   Development of methods for quantifying the pools and fluxes of soil carbon (Parton et al. 1988).

3)   Quantification of carbon pools and fluxes in specific ecosystems under ambient or steady state conditions to develop general principles from the specific examples (Tans et al. 1990).

4)   Characterization and quantification of the factors that control carbon fluxes (Schlesinger et al. 1990).

5)   Development of simulation models that accurately project how carbon fluxes (and thus pools and feedbacks to the atmosphere) will shift in specific ecosystems under different management regimes and under a series of altered climate scenarios (Tans et al. 1990, Dickinson 1986) .

6)   Quantification of the effects of land use and management on soil carbon in tropical, temperate, and forest ecosystems (Burley and Stewart 1985).

7)   Quantification of the economics of implementing soil management practices that sequester and store carbon (Smit et al. 1988, Pritchett and Fisher 1987).

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5.3 Forest Mitigation Compared with Other Biosphere Options

Establishment and management of forests to sequester carbon is one of several options to influence the global carbon cycle (Dixon *in press,c*). Examples of other options are: 1) for terrestrial systems, agroforestry, agriculture, urban forestry, wood lot forestry, and rehabilitation of degraded lands; and 2) for aquatic systems, wetland reconstruction and ocean fertilization (Charles 1989, IPCC 1990, Fulkerson et al. 1989). In most cases, these options would complement, not compete with, forest management for atmospheric carbon mitigation.

5.3.1 Forestry Management Options

The two broad forest management options to sequester carbon are reforestation and improving growth of existing stands (i.e., timber stand improvement or TSI)(Dixon *in press,c*). In Sections 5.1.2 and 5.1.3, the potential of these options was discussed using example analyses for two temperate forest regions in the United States, Douglas-fir in the Pacific Northwest and loblolly pine in the South. The conclusion reached in Section 5.1.3.4 was that for each land unit in these forest regions reforestation can sequester much more carbon than does intensifying management of existing forests.

Assuming this relationship holds for forests in other regions of the world, the potential on a global scale would depend upon the amount of land area available to implement each practice. Estimates of land available for reforestation in the tropics vary (Grainger 1988). A value of 424 million ha was used here in Section 5.1.1.1 to calculate potential carbon sequestration in the tropics. For TSI the figure is unknown, though it is likely to be only a small percentage of the world's closed forests, which encompass about 2700 million ha (Table 1.4-1). Therefore, based upon even these preliminary estimates, reforestation still appears to have substantially more global carbon sequestering potential than TSI. Other factors such as cost and the sociopolitical considerations would also be most important to any comprehensive determination.

5.3.2 Other Forest Management and Terrestrial Options to Sequester Carbon

Other forest management approaches with potential to contribute to global carbon sequestering include: urban tree planting, alternative wood harvesting and utilization methods to retain stored carbon, and plantation establishment for biomass energy through various conversion technologies. Definitive evaluations of these approaches for carbon sequestering are a few years away (Trexler 1990), but preliminary analyses lead to the following tentative conclusions.

Planting trees in urban areas around houses and low buildings can reduce year-round demands for energy from fossil fuels (Grey and Deneke 1978). In the summer in temperate regions, shade trees near buildings reduce air conditioning demands during hot weather. In the winter, trees around houses and other structures used by people act as windbreaks, thereby decreasing heating energy needs (Trexler 1990). Ongoing studies by the United States Department of Energy (DOE) and others are attempting to clarify cost/benefit numbers for urban tree planting on a national basis (Wright *in press*).

Whether started naturally or by planting, forests ultimately mature, and, if they are not harvested, trees senesce and eventually die like all living organisms (Harmon et al. 1990). The wood then oxidizes, releasing carbon back to the atmosphere as CO_2 Durable wood products can continue to store the fixed carbon, but it is estimated that less than half of the wood from harvested trees goes into durable wood products (Harmon et al. 1990), and that the life of most durable wood products is usually a few decades at best. Research and development designed to improve this carbon sink is continuing; examples are improving forest utilization to reduce wood waste, increasing the life of wood products, and expanding wood recycling opportunities (USDA 1990).

The concept of tree plantations as a source of energy has been under study for some time by DOE (Wright *in press*). Of interest are short-rotation woody crops using fast-growing poplar species regenerated from stump sprouts (coppicing) about every eight years. The concept is to harvest wood for burning to generate electricity or to be converted by thermal gasification to ethanol, methanol, biocrude gasoline, and other synthetic liquid or gaseous fuels (Trexler 1990). Though these wood uses release CO_2 to the atmosphere, this would reduce fossil fuel burning, which emits higher amounts of CO_2. Using wood for the above bioenergy purposes is still two or more times more expensive than using fossil fuels, but technological development continues to improve them from the standpoint of economic attractiveness.

Another important tree-growing option is agroforestry or the combination of tree and agricultural crops on the same land unit (MacDicken and Vergara 1990). Estimates of carbon sequestering rates for agroforestry range from 10 to 30 tC/ha/yr (Gregersen et al. 1989). The high end of this range results from mixtures of trees and agronomic crops in a few locations in the tropics; their productivity represents some of the highest carbon sequestering values reported for managed ecosystems (Burley and Stewart 1985). The values include both above- and belowground sequestering and are applicable to the peak years in a crop rotation (i.e., they are not long-term averages). The land available for agroforestry is mostly in the tropics, but definitive estimates of available land are still being developed. Thus, in addition to conventional forest management, there are other options to use trees to mitigate the

buildup of CO_2 in the atmosphere. Each option has multiple benefits similar to forest management and needs much more study and quantification. Eventually comparisons should be made based upon a comprehensive analysis of data that quantifies: 1) the tons of carbon stored annually per ha; 2) the cost per ton of carbon fixed; and 3) the land or water area available for each option (IPCC 1990). Social and environmental impacts must also be evaluated.

Managing lands for agricultural crops can favor carbon in soils. The strategies discussed in Section 5.2 for sequestering carbon in soils (maintaining, restoring, and enlarging soil carbon) also apply here (Parton et al. 1988). In the past, agricultural practices have often depleted soil carbon, resulting in reduced production. For example, temperate grassland soils have about 10 kg C/m^2 (100 tC/ha), but they can lose 30-40% through cultivation in about 20 years (Post et al. 1982, World Resources Institute 1988, Burke et al. 1989). Tropical grasslands start with only 40% of the amount of carbon in temperate soils, but they can be depleted in the same manner (Dregne 1983).

World agricultural lands total 850 million ha, which is generally higher than estimates of land available for reforestation (i.e., 424 million ha, Table 5.1-2). Analyses are needed to define how much of the agricultural lands can, through improved management, attain net gains in carbon while producing profitable crops (Parton et al. 1988, Smit et al. 1988).

Rehabilitating lands with degraded soils offers carbon sequestration opportunities, but fixation rates may be low and costs high compared with forests and agriculture (Barrett-Lennard et al. 1986). However, past land abuses in the world have created an amount of land requiring rehabilitation (1400 million ha) that is greater than the amount of land available for any of the other terrestrial options (Grainger 1988). Ultimately, society will have to confront this option if ever-increasing populations are to be fed and supported (Crosson and Rosenberg 1989). The potential for carbon sequestration by this means may help to accelerate investments in this option (Jain et al. 1989).

5.3.3 Aquatic Options

Much less is known about aquatic options to sequester CO_2. For instance, ocean fertilization is a strategy whereby iron compounds would be added to marine ecosystems to promote phytoplankton populations (Martin and Fitzwater 1988). These organisms would take up CO_2 by photosynthesis and eventually contribute to carbon storage in seafloor sediments. Although potentially effective and economical by first estimates, this method carries unknown ecological risks such as disruption of marine food chains.

Wetlands have, on average, much higher rates of carbon sequestration and storage than do most forest ecosystems. Swamps, marshes, and estuaries have a mean net primary production estimated to be 1000 g $C/m^2/yr$, which is the same level as tropical forests, the most productive of all the world's ecosystem types (Waring and Schlesinger 1985). In addition, swamps and marshes have the highest levels of soil carbon storage in the terrestrial biosphere. Mean soil organic levels are about 69 kg C/m^2, which is more than three times greater than the second highest levels of about 20 kg C/m^2 for grasslands, tundra, and alpine areas (Waring and Schlesinger 1985). These ecosystems are potentially major sources of greenhouse gases (e.g., methane).

Wetlands have greatly diminished in size due to human impacts. For example, Heimlich et al. (1989) stated that "... since European settlement, more than half of the original 215 million acres (87 million ha) have been drained and converted to other land uses," largely for agriculture. The most effective way to manage wetlands for carbon sequestration is to preserve what is remaining. Preservation is expensive because much of the remaining wetlands are in private ownership, so that, in most cases, the landowner must be compensated. In the United States, for example, wetland purchases by federal agencies average about $2000/ha; permanent easements are $700/ha; and rental rates average $40/ha/yr. On former wetlands, restoration is a second approach to managing wetlands, but the costs for restoration are even higher than costs for preservation. Heimlich et al. (1989) report that restoration costs in the United States have ranged from $120/ha to $3000/ha. Research on more efficient methods to manage and/or restore wetlands would likely improve the opportunity to utilize their carbon sequestering capability.

5.3.4 Conclusions

Reforestation or afforestation approaches have a greater potential for sequestering carbon than intensification of forest management. However, land availability is critical for evaluating the potential magnitude of carbon sequestration by reforestation/afforestation.

The largest potential probably lies in the tropics, both in terms of area and potential productivity. Grainger (1988) has estimated that over 700 million ha of land in the tropics could potentially be forested. Although some of this area is semi-arid, much of it is in humid zones and once supported forest cover. Indeed, tropical forests are capable of storing very large amounts of carbon (Evans 1982). Some of this land, however, may have suffered various forms of degradation, and its potential productivity must be evaluated (Jain et al. 1989). To further assess the feasibility of global forestation, a more detailed inventory and classification of available lands is needed.

Any global strategy for reducing atmospheric CO_2 must also address the issue of deforestation (Woodwell et al. 1983). The importance of carbon inputs to the atmosphere from tropical deforestation and burning are well known, although the actual magnitude is uncertain (Woodwell et al. 1983, Detweiler and Hall 1988, Houghton 1990a). It can be said that annual rates of deforestation are in the millions of hectares. Houghton (1990) reported that "... in 1980, the area of tropical forests cleared annually for other uses, largely agricultural, was the size of Pennsylvania," or 11.3 million ha. The World Resources Institute (1990) now estimates that this level of deforestation has almost doubled.

Conserving existing forests is a much more immediate and direct contribution to solving the CO_2 problem than is planting new trees (Harmon et al. 1990, IPCC 1990). This is because existing forests contain levels of biomass and stored carbon not likely to be achieved by plantations (at least not over decade-long periods) and because new plantings can take many years to achieve high growth rates and hence high sequestration rates.

In addition to plantation forestry, variations on forestation practices can be implemented to relieve some of the pressure and demand on the world's forests. These practices include integrated land uses such as agroforestry that use the land more intensively than, for example, shifting cultivation, and they provide a variety of products such as food, fuel, fiber, and fodder (Gregersen et al. 1989). Instituting these practices to increase the productivity of currently underutilized lands will also directly increase the amount of carbon stored in terrestrial vegetation and soils.

A broad-based research program is needed to quantitatively evaluate the potential for sequestering carbon through reforestation and other forest management options. Specific recommendations are listed in Sections 5.1.4 and 5.2.5. In brief, research is needed to determine: 1) land availability, 2) techniques and methods for reforestation and afforestation, 3) actual carbon sequestration rates based on field experiments, and 4) the socioeconomic and environmental effects of a large-scale forestation program.

6 RESEARCH NEEDS AND PLANS

Sections 2 through 5 of this report presented specific research needs for the topics relevant to forest ecosystems. Future research at ERL-C will not be limited to forest ecosystems but will include all dimensions of the terrestrial biosphere. Presented here are three over-arching scientific questions that encompass the entire ERL-C global research program for the next five years. The questions are:

1) How will feedbacks from the terrestrial biosphere amplify or reduce climate change during the next 25-50 years? What are the current and future fluxes of greenhouse gases from the terrestrial biosphere?

2) What are the expected long-term responses of the terrestrial biosphere to global climate change? Who will be the ecological winners and losers?

3) Can the terrestrial biosphere be managed to lessen the impacts of global climate change by increasing carbon sequestration, reducing trace gas fluxes, and promoting a more favorable surface energy balance? What is the potential for wider use of forest management, particularly reforestation, afforestation, and agroforestry?

These three scientific questions emerged through the reviews and research by ERL-C that have been summarized in this report as preliminary results. Over the next five years, the ERL-C effort will continue as a key portion of the broader Global Change Research Program (GCRP) within EPA's Office of Research and Development (ORD). Indeed, these questions and ORD's program will play an important role in the national research program on climate change as outlined by the Committee on Earth and Environmental Sciences (CEES) and in turn by the IPCC (1990).

Full resolution, therefore, of the issues raised by these questions calls for coordination across many organizations and fields of expertise. The process has already begun and will need ongoing attention. The research elements significant to EPA's contribution are outlined as follows.

6.1 Feedback Processes Research (Science Question #1)

Feedbacks to global change from the terrestrial biosphere, and particularly from forests, are significant. Several research priorities have emerged:

1)   Quantify the global carbon cycle, including pools and annual flux. Basically, where is the carbon in the terrestrial biosphere?

2)   Evaluate the role of CO_2 enrichment and its interaction with stress agents on vegetation condition, distribution, and migration.

3)   Assess the current flux of radiatively important gases (CO_2, methane, carbon monoxide, and nonmethane hydrocarbons) from soils and vegetation.

4)   Evaluate the direction and magnitude of physical feedbacks (e.g., reflecting radiation by changes in albedo) to global change.

5)   Determine the emissions of greenhouse gases from forests as positive feedbacks to the atmosphere. Information is needed about forests ranging from vigorous to declining and from natural to managed, within the boreal, temperate, and tropical forest regions.

6.2   Response   Research   (Science   Question   #2)

Ecological impacts due to global change are projected to be significant. Relevant research issues include:

1)   Determining the transient and long-term responses of vegetation (condition, migration, distribution) to global change.

2)   Defining limits of rate of change for various ecosystems (agroecosystems, forests, deserts).

3)   Characterizing the response of hydrologic and energy cycles to global change.

4)   Assessing the impact of global change on terrestrial biodiversity (OTA 1987).

6.3   Mitigation/Adaptation Research   (Science Question #3)

Is it reasonable to expect that increasing ecosystem management throughout the terrestrial biosphere can contribute to the mitigation of global change?   The preliminary results of analyses presented in earlier sections make it appear promising, but research aimed at reducing the uncertainty is the next step.   Within EPA/ORD, ERL-C plans call for research beginning in FY91 to provide the following information:

1)   Improved data on the land area in the world that is available and suitable for more intensive ecosystem management to sequester atmospheric carbon;

2)   Carbon sequestering rates and the potential for storage of carbon above- and belowground for management options, including afforestation, agroforestry, and fuel wood forestry programs in the boreal, temperate, and tropical regions;

3)   A clear understanding of the global carbon cycle relative to natural and managed forest ecosystems throughout the world;

4)   More effective technology for the propagation and silvicultural management of a wider array of forest species to increase the cropping options across the mix of available lands;

5)   Refined projections about global warming, including climate scenarios to determine how the health and productivity of future forests will vary by location;

6)   Data about the response of forests to elevated levels of atmospheric CO_2, with emphasis on photosynthesis, WUE, and net ecosystem production;

7)   Effective techniques to manage forest soils to maintain, restore, and enlarge their carbon sequestration rates and storage capacity;

8)   Improved knowledge of biodiversity trends associated with natural and managed forests as the forests change in response to future global climates;

9)   Case studies showing how forest management, particularly reforestation and agroforestry, can aid in offsetting both deforestation and large-scale forest decline resulting from global climate change or changing land use that reduces the amount of productive land;

10)   Conceptual models based on a Geographic Information System (GIS) analysis to integrate results from the above research and to provide projections of the contributions of forest management on a world scale as an aid to mitigation of increases in atmospheric CO_2; and

11)   An assessment of the contribution of forest management to carbon sequestering in the broader concept of managing the biosphere for a sustainable living environment.

6.4   Field Assessment of Forest and Agroforestry Management Opportunities to Sequester Atmospheric CO_2

6.4.1 Goal

The goal of the assessment is to field test the feasibility of increasing carbon storage in the terrestrial biosphere through managing the carbon cycle; i.e., increasing both above- and belowground carbon storage through forestry, agroforestry, and agricultural practices.

6.4.2 Rationale

This study would accelerate implementation of field demonstration trials for terrestrial management options upon completion of the feasibility study. The aim is to be ready for early on-the-ground testing as soon as clear guidance is available.

6.4.3 Approach

The strategy will be to establish a network of field trials in major global biomes to determine the biologic and economic feasibility of managing terrestrial carbon pools and fluxes. The trials are expected to be established in representative forestry, agroforestry, and agricultural areas of the boreal, temperate, and tropical regions. Research will be coordinated with existing groups such as the Food and Agriculture Organization (FAO) of the United Nations, United States Agency for International Development (USAID), and others. Key components of this study are:

1)   Institute a system of research field trials on unmanaged or poorly managed lands In forested, agroforested, and agricultural regions to quantify the potential for expanding terrestrial carbon sequestration. Degraded lands will be emphasized.

2)   Initiate a worldwide system of field surveys in all major biomes to determine the carbon sequestering potential of representative forested, agroforested, and agricultural areas presently under management.

6.4.4 Product

In this study, demonstration sites and field trials will be established to: 1) quantify the carbon sequestering capability of managed forestry, agroforestry, and agricultural areas in the world; and 2) estimate the potential to optimize that capability through more intensive management practices.

6.5   Assessment and Validation of Terrestrial Biosphere Models of Global Change Feedbacks and Responses

6.5.1 Goal

The goal of this study is to design and implement process research projects to allow better evaluations and simulations of terrestrial biosphere management options. Ecophysiological factors and processes t· regulate pools of carbon and exchange of greenhouse gases via vegetation and soils will b· studied. Research in a minimum of five sites in the each of the following biomes will be establishec wet tropical forest; temperate deciduous forest; xeromorphic shrubland; estuarine wetland; mixed sub-boreal forest; and boreal forest.

6.5.2 Rationale

Long-term assessments are needed to validate and calibrate large-scale models of globa. :   nge and terrestrial biospheric responses and feedbacks. A wide range of biomes should be evaluated because ecological responses and feedbacks of climate change are expected to vary. Present mechanistic models do not incorporate the effects of global change on ecophysiological processes such as photosynthesis, transpiration, respiration, and growth, and large-scale models such as GCMs do not Incorporate any biological process.

6.5.3 Approach

Research will be established in representative biomes to assess carbon cycling processes. A range of instruments and field exposure facilities will be used to assess above- and belowground processes (meteorological, plant gas-exchange, soil biogeochemistry). This approach allows a determination of system-level responses to abiotic and biotic stresses under present and enriched CO_2 regimes and under management scenarios. Data collected will be used to calibrate and validate large-scale models (e.g., GCMs).

6.5.4 Product

The outcome of this research will be General Circulation Model/Global Vegetation Model predictions of biome specific responses and feedbacks to climate change. The GCMs will be calibrated and validated from long-term data collected in the field.

7   LITERATURE CITED

Ajtay, G.L., P. Ketner, and P. Duvigneaud.   1979. Terrestrial primary production and phytomass, pp. 129-182. In: The Global Carbon Cycle. SCOPE Report No. 13. John Wiley, Chichester.

Allen, J.C. 1985. Soil response to forest clearing in the United States and the tropics: Geological and biological factors. Biotropics 17:15-27.

Allen, L.H. Jr. 1990. Plant responses to rising carbon dioxide and potential interactions with air pollutants. J. Environ. Qual. 19(1):15-34.

Allen, T.F.J., and T.B. Starr. 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press, Chicago.

Armentano, T.V., and C.W. Ralston. 1980. The role of temperate zone forests in the global carbon cycle. Can. J. For. Res. 10:53-60.

Arno, S.F. 1984. Timberline: Mountain and Arctic Forest Frontiers. The Mountaineers, Seattle, WA.

Arnone, J.A., and J.C. Gordon. In press. Effect of nodulation, nitrogen fixation and CO_2 enrichment on the physiology, growth and dry mass allocation of Alnus rubra seedlings. New Phytol.

Attiwill, P.M. 1986. Interactions between carbon and nutrients in the forest ecosystem. Tree Physiol. 2:389-399.

AuClair, A.N.D. 1985. Postfire regeneration of plant and soil organic pools in a Picea mariana-Cladonia stellaris ecosystems. Can. J. For. Res. 15:279-291.

Bailey, J.D., R.K. Dixon, and R.W. Rose. 1990. Dormancy and cold-hardiness of Pseudotsuga menziesii, Alnus rubra, and Acer macrophyllum in an enriched-carbon dioxide environment. 11th North American Forest Biology Workshop, June 13-15, Athens, GA.

Ballard, R. 1981. Optimum nitrogen rates for fertilization of loblolly pine plantations. Southern J. Appl. For. 5:212-216.

Ballard, R., and J.S. Shumway. 1986. Soil and site information for optimum management of Douglas-fir, pp. 168-176. In: C.O. Oliver, D.P. Hanley, and J.A. Johnson, eds. Douglas-fir: Stand Management for the Future. College of Forest Resources, University of Washington, Seattle, WA.

Ballard, R., H.W. Duzan, and M.B. Kane. 1981. Thinning and fertilization of loblolly pine plantations, pp.100-104. In: J.P. Barnett, ed. Proceedings of the First Biennial Southern Silviculture Research Conference. General Technical Report SO-34, USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA.

Barker, J.R., S. Henderson, R.F. Noss, and D.T. Tingey. In press. Biodiversity and human impacts. In: W.A. Nierenberg, ed. Encyclopedia of System Science, Academic Press, San Diego, CA.

Barrett, J.W., ed. 1980. Regional Silviculture of the United States. John Wiley, New York. 551 pp.

Barrett-Lennard, E.G., C.V. Malcolm, W.R. Stern, and S.M. Wilkins, eds. 1986. Forage and Fuel Production from Salt-Affected Wasteland. Elsevier Publishers, New York. 459 pp.

Benson, R.E. 1982. Management consequences of alternative harvesting and residue treatment practices - lodgepole pine. General Technical Report INT-132, USDA Forest Service.

Berry, J. and O. Bjorkman. 1980. Photosynthetic response and adaptation to temperature in higher plants. Ann. Rev. Plant Physiol. 31:491-543.

Binkley, D., K. Cromack Jr., and R. Friedriksen. 1982. Nitrogen accretion and availability in some snowbrush ecosystems. For. Sci. 28:720-724.

Böhm, W. 1979. Methods of Studying Root Systems. Springer-Verlag, Berlin. 188 pp.

Bolin, B. 1983. The carbon cycle, pp. 41-45. In: The Major Biogeochemical Cycles and Their Interactions. SCOPE Report No. 21. John Wiley, Chichester.

Bolin, B., E.T. Degens, S. Kempe, and P. Ketner. 1979. The Global Carbon Cycle. John Wiley & Sons, New York.

Bonan, G.B. 1988. Environmental Processes and Vegetation Patterns in Boreal Forests. Ph.D. Dissertation. University of Virginia, Charlottesville, VA.

Bonan, G.B. 1989. A computer model of the solar radiation, soil moisture, and soil thermal regimes in boreal forests. Ecol. Modelling 45:275-306.

Bonan, G.B. and H.H. Shugart. 1989. Environmental factors and ecological processes in boreal forests. Ann. Rev. Ecol. Sys. 10:1-28.

Bonan, G.B., H.H. Shugart, and D.L. Urban. 1990. The sensitivity of some high-latitude boreal forests to climatic parameters. Climatic Change 16:9-30.

Bormann, F.H., and G.E. Likens. 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York. 256 pp.

Botkin, D.B., and L.G. Simpson. 1990. Biomass of the North American boreal forest: A step toward accurate global measures. Biogeochemistry 9:161-174.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1972. Some ecological consequences of a computer model of forest growth. J. Ecol. 60:849-873.

Box, E.O. 1981. Macroclimate and Plant Forms: An Introduction to Predictive Modeling in Phytogeography. Dr. W. Junk Publishers, The Hague.

Brown, K., and K.O. Higginbotham. 1986. Effects of carbon dioxide enrichment and nitrogen supply on growth of boreal tree seedlings. Tree Physiol. 2:223-232.

Brown, S., A.E. Lugo, and J. Chapman. 1986. Biomass of tropical tree plantations and its implications for the global carbon budget. Can. J. For. Res. 16:390-394.

130

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. Soil Sci. Soc. Amer. J. 53:800-805.

Burke, M.J., L.V. Gusta, H.A. Quamme, C.J. Weiser, and P.H. Li. 1976. Freezing injury in plants. Ann. Rev. Plant Physiol. 27:507-528.

Burkhart, H.E., K.D. Farrar, R.L. Amateis, and R.F. Daniels. 1987. Simulation of individual tree growth and stand development in loblolly pine plantations on cutover, site-prepared areas. Publication FWS-1-87, School of Forest and Wildlife Resources, Virginia Polytechnic Institute and State University, Blacksburg, VA. 25 pp.

Burley, J., and J. Stewart. 1985. Increasing Productivity of Multipurpose Trees. International Union of Forest Research Organizations, Vienna, Austria. 560 pp.

Campagna, M.A., and H.A. Margolis. 1989. Influence of short-term atmospheric CO_2 enrichment on growth, allocation patterns, and biochemistry of black spruce seedlings at different stages of development. Can. J. For. Res. 19:773-782.

Canham, A.E., and W.J. McCavish. 1981. Some effects of CO_2, daylength and nutrition on the growth of young forest tree plants: In the seedling stage. Forestry 54(2):169-182.

Cess, R.D., G.L. Potter, J.P. Blanchet, G.J. Boer, S.J. Ghan, J.T. Kiehl, H. Le Treut, Z.-X Li, X.-Z Liang, J.F.B. Mitchell, J.-J Morcrette, D.A. Randall, M.R. Riches, E. Roeckner, U. Schlese, A. Slingo, K.E. Taylor, W.M. Washington, R.T. Wetherald, and I. Yagai. 1989. Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. Science 245:513-516.

Charles, D. 1989. EPA's plan for cooling the global greenhouse. Science 243:1544-1545.

Cofer, W.R., J.S. Levine, D.I. Sebacher, E.L. Winstead, P.J. Riggan, B.J. Stocks, J.A. Brass, V.G. Ambrosia, and P.J. Boston. 1989. Trace Gas Emissions from Chaparral and Boreal Forest Fires. J. Geophys. Res. 94:2255-2259.

Comerford, N.B., R.F. Fisher, and W.L. Pritchett. 1982. Advances in forest fertilization on the southeastern coastal plain, pp. 370-378. In: R. Ballard and S.P. Gessel, eds. IUFRO Symposium on Forest Site and Continuous Productivity. General Technical Report PNW-163, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Conroy, J.P., M. Küppers, B. Küppers, J. Virgona, and E.W.R. Barlow. 1988. The influence of CO_2 enrichment, phosphorus deficiency and water stress on the growth, conductance and water use of Pinus radiata D. Don. Plant Cell Environ. 1:91-98.

Cook, R.E. 1969. Variation in species density of North American birds. Syst. Zool. 18:63-84.

Cooper, D.J. 1986. Trees above and beyond tree line in the Arrigetch Peaks region, Brooks Range, Alaska. Arctic 39(3):247-252.

Cooperative Holocene Mapping Project (COHMAP). 1988. Climatic changes of the last 18,000 years: Observations and model simulations. Science 241:1043-1052.

131

Cowan, I.R. 1965. Transport of water in the soil-plant-atmosphere system. J. Appl. Ecol. 2:221-239.

Cramer, W., and R. Leemans. In press. Assessing impacts of climate change on vegetation using global vegetation models. In: Shugart, H.H. and A.M. Solomon, eds. Vegetation Dynamics Modelling and Global Change. Chapman-Hall, New York.

Cropper, W.P. Jr. 1987. Labile carbon dynamics in a Florida slash pine plantation, pp. 278-284. In: A.R. Ek, S.R. Shifley, and T.E. Burk, eds. Forest Growth Modelling and Prediction Proceedings, August, 1987. General Technical Report NC-120, USDA Forest Service, North Central Forest Experiment Station.

Cropper, W.P. Jr., and K.C. Ewel. 1983. Computer simulation of long-term carbon storage patterns in Florida slash pine plantations. For. Ecol. Manage. 6:101-114.

Cropper, W.P. Jr., and K.C. Ewel. 1984. Carbon storage patterns in Douglas-fir ecosystems. Can. J. For. Res. 14:855-859.

Cropper, W.P. Jr., and K.C. Ewel. 1987. A regional carbon storage simulation for large-scale biomass plantations. Ecol. Model. 36:171-180.

Crosson, P.R., and N.J. Rosenburg. 1989. Strategies for agriculture. Sci. Amer. 261:128-135.

Crutzen, P.J. 1988. Variability in atmospheric-chemical systems. In: T. Rosswall, R.G. Woodmansee and P.G. Risser, eds. Scales and Global Change. John Wiley & Sons Ltd., New York, NY.

Currie, D.J., and V. Paquin. 1987. Large-scale biogeographical patterns of species richness of trees. Nature 329:326-329.

Curtis, P.S., B.G. Drake, P.W. Leadley, W.J. Arp, and D.F. Whigham. 1989a. Growth and senescence in plant communities exposed to elevated CO_2 concentrations on an estuarine marsh. Oecologia 78:20-26.

Curtis, P.S., B.G. Drake, and D.F. Whigham. 1989b. Nitrogen and carbon dynamics in C_3 and C_4 estuarine marsh plants grown under elevated CO_2 in situ. Oecologia 78:297-301.

Curtis, R.O., G.W. Clendenen, D.L. Reukema, and D.J. DeMars. 1982. Yield tables for managed stands of coast Douglas-Fir. General Technical Report PNW-135, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Dangerfield, J., and H. Brix. 1981. Comparative effects of ammonium nitrate and urea fertilizers on tree growth and soil processes, pp. 133-139. In: S.P. Gessel, R.M. Kenady, and W.A.J. Atkinson, eds. Proceedings, Forest Fertilization Conference. University of Washington. Canadian Forestry Service, Victoria BC.

Davis, K.P. 1966. Forest Management: Regulation and Valuation. McGraw-Hill, New York. 519 pp.

Davis, M.B. 1981. Quaternary history and the stability of forest communities. In: D.C. West, H.H. Shugart, and D.B. Botkin, eds. Forest Succession: Concepts and Application. Springer-Verlag, NY. 517 pp.

Davis, M.B., K.D. Woods, S.L. Webb, and R.P. Futyma. 1986. Dispersal versus climate: expansion of *Fagus* and *Tsuga* into the Upper Great Lakes region. Vegetatio 67:93-103.

DeLucia, E.H., and S.A. Heckathorn. 1989. The effect of soil drought on water-use efficiency in a contrasting Great Basin desert and Sierran montane species. Plant Cell Environ. 12:935-940.

Detwiler, R.P., and C.A.S. Hall. 1988. Tropical forests and the global carbon cycle. Science 239:42-46.

Dickinson, R.E. 1986. How will climate change: The climate system and modelling of future climate, pp. 221-231. In: B. Bolin, B.R. Döös, J. Jäger, and R.A. Warrick, eds. Scope 29: The Greenhouse Effect, Climatic Change and Ecosystems. John Wiley, New York.

Dickinson, R.E. 1989. Uncertainties of estimates of climatic change: A review. Climatic Change 15:5-13.

Dixon, R.K. In press,a. Feedbacks and response of boreal forests to global change. In: A. Shivendko, ed. Proceedings of Boreal Forest Symposium. Arkhanglesk, USSR.

Dixon, R.K. In press,b. Regional forest management planning in the southern U.S. In: Proceedings of North American Conference on Forestry Response to Climate Change, Climate Institute, Washington, DC.

Dixon, R.K. In press,c. Response and feedbacks of global forests to climate change. In: Management and Productivity of Western-Montane Forest Soils, General Technical Report, USDA Forest Service, IRS. In press.

Dixon, R.K., R.S. Meldahl, G.A. Ruark, and W.G. Warren. 1990. Process Modeling of Forest Growth Responses to Environmental Stress. Timber Press, Portland, OR 441 p.

Dixon, R.K., G.M. Wright, G.T. Behrns, R.D. Teskey, and T.M. Hinckley. 1980. Water deficits and root growth of ectomycorrhizal white oak seedlings. Can. J. For. Res. 10:545-548.

Drake, B.G., P.W. Leadley, W. Arp, D. Nassiry, and P.S. Curtis. Submitted. Testing the effects of elevated CO_2 on natural vegetation. I. Control of CO_2 and microclimate inside an open top chamber. Functional Ecology.

Drake, B.G., P.S. Curtis, W.J. Arp, P.W. Leadly, J. Johnson, and D. Whigham. 1987. Effects of elevated carbon dioxide on Chesapeake Bay wetlands. III. Ecosystem and whole plant responses in the first year of exposure. U.S. Department of Energy, Carbon Dioxide Research Division Report 044, Office of Energy Research, Washington, DC, 20545.

Dregne, H.E. 1983. Desertification of Arid Lands. Harwood Academic Publishers, New York, NY. 242 pp.

Duxbury, J.M., M.S. Smith, J.W. Doran, C. Jordan, L. Scott, and E. Vance. 1989. Soil organic matter as a source and a sink of plant nutrients. In: D.C. Coleman, J.M. Oades and G. Uehara, eds. Dynamics of Soil Organic Matter in Tropical Ecosystems. Niftal Project, University of Hawaii Press, Honolulu, HI.

Dyson, F.J. 1977. Can we control the carbon dioxide in the atmosphere? Energy 2:287-291.

Eamus, D., and P. Jarvis. 1989. The direct effects of increase in the global atmospheric CO_2 concentration on natural and commercial temperate trees and forests. Adv. Ecol. Res. 19:2-56.

Edmonds, R.L. 1987. Decomposition rates and nutrient dynamics in small-diameter woody litter in four forest ecosystems in Washington, U.S.A. Can. J. For. Res. 17:499-509.

Edwards, M.E. and P.W. Dunwiddie. 1985. Dendrochronological and palynological observations on *Populus balsamifera* in northern Alaska, U.S.A. Arctic and Alpine Research 17:271-278.

Edwards, M.E., P.M. Anderson, H.L. Garfinkel, and L.B. Brubaker. 1985. Late Wisconsin and Holocene vegetational history of the Upper Koyukuk region, Brooks Range, Alaska. Can. J. Bot. 63:616-626.

Emanuel, W.R. 1985. Response to comment: Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Climatic Change 7:457-460.

Emanuel, W.R., G.G. Killough, W.M. Post, and H.H. Shugart. 1984. Modeling terrestrial ecosystems in the global carbon cycle with shifts in carbon storage capacity by land-use change. Ecology 65:970-983.

Emanuel, W.R., H.H. Shugart, and M.P. Stevenson. 1985. Climatic change and the broad-scale distribution of terrestrial ecosystem complexes. Climate Change 7:29-43.

Evans, J. 1982. Plantation Forestry in the Tropics. Clarendon Press, Oxford. 472 pp.

Fahnestock, G.R., and J.K. Agee. 1983. Biomass consumption and smoke production by prehistoric and modern forest fires in western Washington. J. For. 653-657.

Fajer, E.D., M.D. Bowers, and F.A. Bazzaz. 1989. The effects of enriched carbon dioxide atmospheres on plant-insect herbivore interactions. Science 243:1198-1200.

Farnum, P., R. Timmis, and J.L. Kulp. 1983. Biotechnology of forest yield. Science 219:694-702.

Federer, C.A. 1982. Transpirational supply and demand: plant, soil, and atmospheric effects evaluated by simulation. Water Resour. Res. 18(2):355-362.

Food and Agriculture Organization (FAO). 1985. Topical forestry action plan. Food and Agriculture Organization of the United Nations, Rome. 275 pp.

Foreward, P.W., R.S. Moulton, and J.D. Snellgrove. 1990. FY89 U.S. Forest Service Planting Report. USDA Forest Service, Coop. Forestry, Washington, DC. 15 pp.

Fulkerson, W., D.B. Reister, A.M. Perry, A.T. Crane, D.E. Kash, and S.I. Auerbach. 1989. Global warming: An energy technology R&D challenge. Science 246:868-869.

Funsch, R.W., R.H. Mattson, and G.R. Mowry. 1970. CO_2-supplemented atmosphere increases growth of *Pinus strobus* seedlings. For. Sci. 16:459-460.

Garfinkel, H.L. and L.B. Brubaker. 1980. Modern climate-tree-growth relationships and climatic reconstruction in sub-Arctic Alaska. Nature 286:872-874.

Gates, W.L. 1985. Modeling as a means of studying the climate system. In: M.C. MacCracken and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE/ER-0237, US Department of Energy, Washington, DC.

Giddens, J. 1957. Rate loss of carbon from Georgia soils. Soil Sci. Soc. Amer. Proc. 21:513-515.

Gjerstad, D.H., L.R. Nelson, J.H. Dukes, and W.A. Retzlaff. 1984. Vegetation management, pp. 247-258. In: M.L. Duryea, and G.N. Brown, eds. Seedling Physiology and Reforestation Success. Proceedings of the Physiology Working Group Technical Session. Soc. Amer. Foresters. Nijhoff/Junk Publishers, Boston, MA.

Goldstein, G.H. 1981. Ecophysiological and demographic studies of white spruce (Picea glauca (Moench) Voss) at treeline in the central Brooks Range of Alaska. Ph.D. Thesis, University of Washington. 193 pp.

Goldstein, G.H., Brubaker, L.B. and T.M. Hinckley. 1985. Water relations of white spruce (Picea glauca (Moench) Voss) at tree line in north central Alaska. Can. J. For. Res. 15:1080-1087.

Grainger, A. 1988. Estimating areas of degraded tropical lands requiring replenishment of forest cover. Int. Tree Crops J. 5:31-61.

Green, K., and R. Wright. 1977. Field response of photosynthesis to CO_2 enhancement in ponderosa pine. Ecology 58:687-692.

Greenland, D.J., and P.H. Nye. 1959. Increases in the carbon and nitrogen contents of tropical soils under natural fallows. J. Soil Sci. 10:284-299.

Gregersen, H., S. Draper, and D. Elz. 1989. People and trees: The role of social forestry in sustainable development. EDI Seminar Series. World Bank, Washington, DC. 273 pp.

Grey, G.W., and F.J. Deneke. 1978. Urban Forestry. John Wiley & Sons, New York, NY. 175 pp.

Grotch, S.L., ed. 1988. Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data. U.S. Dept. of Energy Report TR041, Washington, DC. 291 pp.

Hansen, J., A. Lacis, D. Rind, G. Russel, P. Stone, I. Fung, and J. Lerner. 1984. Climate sensitivity: Analysis of feedback mechanism. In: Climate Processes and Climate Sensitivity, Geophys. Monogr. Ser., AGU, Washington, DC. 29:130-163.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, and G. Russell. 1988. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. J. Geophys. Res. 93:9341-9364.

Hansen-Bristow, K.J. 1986. Influence of increasing elevation on growth characteristics at timberline. Can. J. Bot. 64:2517-2523.

Hansen-Bristow, K.J., and J.D. Ives. 1984. Changes in the forest-alpine tundra ecotone: Colorado Front Range. Phys. Geog. 5:186-197.

Hansen-Bristow, K.J. and J.D. Ives. 1985. Composition, form and distribution of the forest-alpine tundra ecotone, Indian Peaks, Colorado, U.S.A. Erdkunde 39:286-295.

Hare, F.K. 1950. Climate and zonal divisions of the boreal forest formation in eastern Canada. Geog. Rev. 40:615-635.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699-702.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack Jr., and K.W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15:133-302.

Harvey, L.D.D. 1988. Climatic impact of ice-age aerosols. Nature 334:333-336.

Harvey, L.D.D. 1989. Transient climatic response to an increase of greenhouse gases. Climatic Change 15:15-30.

Heimlich, R.E., M.B. Carey, and R.J. Brazee. 1989. Beyond swampbuster: A permanent wetland preserve. J. Soil Water Conserv. 9:445-450.

Henderson, S., R.K. Olson, and R.F. Noss. 1989. Current and potential threats to biodiversity in forests of the lower Pacific Coast states. pp. 325-336. In: R.K. Olson and A.S. Lefohn, eds., Effects of Air Pollution on Western Forests, Air and Waste Management Association, Anaheim, CA.

Hermann, R.K. 1977. Growth and productivity of tree roots: A review, pp. 7-28. In: J.K. Marshall, ed. The Below-Ground Ecosystem: A Synthesis of Plant-Associated Processes. Colorado State University, Fort Collins, CO.

Higginbotham, K.O., J.M. Mayo, S. L'Hirondelle, and D.K. Krystofiak. 1985. Physiological ecology of lodgepole pine (Pinus contorta) in an enriched CO_2 environment. Can. J. For. Res. 15:417-421.

Holdridge, L.R. 1947. Determination of world formulations from simple climatic data. Science 105:367-368.

Holdridge, L.R. 1967. Life Zone Ecology. Tropical Science Center, San Jose, CA.

Hollinger, D.Y. 1987. Gas exchange and dry matter allocation responses to elevation of atmospheric CO_2 concentration in seedlings of three tree species. Tree Physiol. 3:193-202.

Houghton, R.A. 1987. Terrestrial metabolism and atmospheric CO_2 concentrations. BioScience 37:672-678.

Houghton, R.A. 1990a. The global effects of tropical deforestation. Environ. Sci. Technol. 24(4):414-422.

Houghton, R.A. 1990b. The future role of tropical forests in affecting the carbon dioxide concentration of the atmosphere. Ambio. 19:204-209.

Houghton, R.A., and G.M. Woodwell. 1989. Global climatic change. Sci. Amer. 260:36-44.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. Ecol. Monogr. 53:235-262.

Houghton, R.A., R.D. Boone, J.M. Melillo, C.A. Palm, G.M. Woodwell, N. Myers, B. Moore III, and D.K. Skole. 1985. Net flux of carbon dioxide from tropical forests in 1980. Nature 316:617-620

Houghton, R.A., R.D. Boone, J.R. Fruci, J.E. Hobbie, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, and G.M. Woodwell. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographic distribution of the global flux. Tellus 39B:122-139.

Houpis, J.L.J., K.A. Surano, and J. Shinn. 1987. Seasonal and diurnal water use patterns of *Pinus ponderosa* seedlings exposed for two years with elevated carbon dioxide. Plant Physiol. (suppl) 83:45.

Houpis, J.L.J., K.A. Surano, S. Cowles, and J.H. Shinn. 1988. Chlorophyll and carotenoid concentrations in two varieties of *Pinus ponderosa* seedlings subjected to long-term elevated carbon dioxide. Tree Physiol. 4:187-193.

Husch, B., C.I. Miller, and T.W. Beers. 1972. Forest Mensuration. Ronald Press, New York, 410 pp.

ICF, Inc. 1989. Summary Report: Scenarios Advisory Meeting Report, 31 Aug-1 Sept, Boulder, CO. Report for U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC, 14 pp.

Ino, Y., and M. Monsi. 1969. An experimental approach to the calculation of CO_2 amount evolved from several soils. Jap. J. Bot. 2:153-188.

Intergovernmental Panel on Climate Change (IPCC). 1990. Scientific Assessment of Climate Change. Report for WGI Plenary Meeting.

Ives, J.D., and K.J. Hansen-Bristow. 1983. Stability and instability of natural and modified upper timberline landscapes in the Colorado Rocky Mountains, U.S.A. Mountain Research Division 3:149-155.

Jain, R.K., K. Paliwal, R.K. Dixon, and D.H. Gjerstad. 1989. Improving productivity of multipurpose trees growing on substandard soils in India. J. For. 87:38-42.

Jarvis, P.G. 1987. Water and carbon fluxes in ecosystems, pp. 50-67. In: E.D. Shulze and H. Zwolfer, eds. Potentials and Limitations of Ecosystem Analysis, Springer-Verlag, Berlin.

Jarvis, P.G., and K.G. McNaughton. 1986. Stomatal control of transpiration: scaling up from leaf to region. Adv. Ecol. Res. 15:1-49.

Jenkinson, D.S., and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123:298-305.

Johnson, E.A. Personal communication. Department of Biology, University of Calgary, Calgary, Alberta.

Jordan, C.F., ed. 1989. Man and the Biosphere Series. Volume 2: An Amazonian Rain Forest: The Structure and Function of a Nutrient Stressed Ecosystem and the Impact of Slash-and-Burn Agriculture. UNESCO and the Parthenon Publishing Group.

Keane, R.E., S.F. Arno, and J.K. Brown. 1989. FIRESUM: An ecological process model for fire succession in western conifer forests. General Technical Report, INT-266, USDA Forest Service, Intermountain Research Station.

Keeling, C.D., R.B. Bacastow, A.F. Carter, S.C. Piper, T.P. Whorf, M. Heimann, W.G. Mook, and H. Roelofffzen. 1989. A three-dimensional model of atmospheric CO_2 transport based on observed winds: Analysis of observational data. Geophys. Monogr. 55:165-236.

Keyfitz, N. 1989. The growing human population. Sci. Amer. 261:119-126.

Kiester, A.R. 1971. Species density of North American amphibians and reptiles. Syst. Zool. 20:49-67.

King, A.W, D.L. DeAngelis, and W.M. Post. 1987. The seasonal exchange of carbon dioxide between the atmosphere and the terrestrial biosphere: Extrapolation from site-specific models to regional models. Publication 2988, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN.

Kira, T. 1965. Primary production in forests, pp. 5-40. In: J.P. Cooper, ed. Photosynthesis and Productivity in Different Environments. Cambridge University Press, England.

Köppen, W. 1900. Versuch einer Klassification der Klimate, vorzugsweise nach ihren Beziehungen zur pflanzenwelt. Geographische Zeitschrift. 6:593-611, 657-679.

Köppen, W. 1918. Klassification der Klimate nach Temperatur, Neidenschlag und Jahreslauf. Petermanns Geogr. Mitt. 64:193-203, 243-248.

Köppen, W. 1936. Das Geographische System der Klimate. In: W. Köppen, and R. Geiger, Handbuch der Klimatologie, IC, Gebr Borntraeger, Berlin, 46 pp.

Kramer, P.J. 1983. Water Relations of Plants. Academic Press, New York, NY. 489 pp.

Kramer, P.J., and N. Sionit. 1987. Effects of increasing carbon dioxide concentration on the physiology and growth of forest trees, pp. 219-246. In: W.E. Shands and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. The Conservation Foundation, Thomson-Shore, Inc., Dexter, MI.

LaMarche, V.C., Jr., and H.A. Mooney. 1967. Altithermal timberline advance in the western United States. Nature 13:980-982.

Larsen, J.A. 1989. The Northern Forest Border in Canada and Alaska. Springer-Verlag, New York. 255 pp.

Lashof, D.A. 1987. The role of the biosphere in the global carbon cycle: evaluation through biospheric modeling and atmospheric measurement. Ph.D. Dissertation, Energy and Resources Group, University of California, Berkeley, CA.

Lashof, D.A. 1989. The dynamic greenhouse: Feedback processes that may influence future concentrations of atmospheric trace gases and climatic change. Climatic Change 14:213-242.

Lashof, D.A., and D.A. Tirpak. 1989. Policy Options for Stabilizing Global Climate. Draft Report to Congress, U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC.

Leemans, R. 1990. Possible changes in natural vegetation patterns due to a global warming. Publication No. 108, International Institute for Applied Systems Analysis A-2361, Laxenburg, Austria. 13 pp.

Leemans, R., and I.C. Prentice. 1989. FORSKA: A general forest succession model. Institute of Ecological Botany, Uppsala, Sweden.

Lev, D.J. 1987. Balsam poplar (Populus balsamifera) in Alaska: Ecology and growth response to climate. Master's Thesis, University of Washington, Seattle, WA. 69 pp.

Leverenz, J.W., and D.J. Lev. 1987. Effects of carbon dioxide-induced climate changes on the natural ranges of six major commercial tree species in the western United States, pp. 123-155. In: W.E. Shands and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. The Conservation Foundation, Thomson-Shore, Inc., Dexter, MI.

Lonqjun, G. circa 1986. Green China. Office of Central Afforestation Committee. The Great Wall Publishing House. 31 pp.

Lugo, A.E., and S. Brown. 1986. Steady state terrestrial ecosystems and the global carbon cycle. Vegetatio 68:83-90.

Luxmoore, R.J., E.G. O'Neill, J.M. Ells, and H.H. Rogers. 1986. Nutrient uptake and growth responses of Virginia pine to elevated atmospheric carbon dioxide. J. Environ. Qual. 15:244-251.

MacDicken, K.G., and N.T. Vergara. 1990. Agroforestry: Classification and Management. John Wiley & Sons, New York, NY. 382 pp.

Manabe, S., and R.J. Stouffer. 1980. Sensitivity of a global climate to an increase of CO_2 concentration in the atmosphere. J. Geophys. Res. 85:5529-5554.

Manabe, S., and R.T. Wetherald. 1987. Large-scale changes in soil wetness induced by an increase in carbon dioxide. J. Atmos. Sci. 44:1211-1235.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279-288.

Manne, A.S., and R.G. Richels. In press,a. CO_2 emission limits: an economic cost analysis for the USA. Energy J.

Manne, A.S., and R.G. Richels. In press,b. Global CO_2 emission reductions: The impacts of rising energy costs. Energy J.

Marks, D. Submitted. The sensitivity of potential evapotranspiration to climate change over the continental United States.

Marland, G. 1988. The prospect for solving the CO_2 problem through reforestation. DOE/NBB-0082, U.S. Department of Energy, Office of Energy Research, Washington, DC. 66 pp.

Marland, G. 1989. The role of forests in addressing the CO_2 greenhouse. In: J.C. White, ed. Global Climate Change Linkages: Acid Rain, Air Quality and Stratospheric Ozone. Elsevier Publishing, New York.

Martin, J.H., and S.E. Fitzwater. 1988. Iron deficiency limits phytoplankton growth in the northeast Pacific subarctic. Nature. 331:341-343.

Materna, J. 1989. Air pollution and forestry in Czechoslovakia. Environ Monitor. Assess. 12:227-235.

Matthews, E. 1983. Global vegetation and land use: New high-resolution data base for climate studies. J. Climate Appl. Meteorol. 22:474-487.

Mattson, K.G., and W.T. Swank. 1989. Soil and detrital carbon dynamics following forest cutting in the southern Appalachians. Biol. Fert. Soils 7:247-253.

Mattson, W.S., and A. Addy. 1975. Phytophagous insects as regulators of forest primary productivity. Science 190:515-521.

Meehl, G.A., and Washington, W.M. 1990. CO_2 climate sensitivity and snow-sea-ice albedo parameterization in an atmospheric GCM coupled to a mixed-layer ocean model. Climatic Change 16:283-306.

Melillo, J.M., J.D. Aber, and J.F. Muratore. 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63:621-626.

Miller, J.H., and D.L. Sirois. 1986. Soil disturbance by skyline yarding vs. skidding in a loamy hill forest. Soil Sci. Soc. Amer. J. 50:1579-1583.

Miller, R.E., and S.R. Webster. 1979. Fertilizer response in mature stands of Douglas-fir, pp. 126-132. In: S.P. Gessel, R.M. Kenady, and W.A. Atkinson, eds. Proceedings: Forest Fertilization Conference. College of Forest Resources, University of Washington, Seattle, WA.

Miller, R.E., P.R. Barker, C.E. Peterson, and S.R. Webster. 1986. Using nitrogen fertilizers in management of coast Douglas-fir: Regional trends of response, pp. 290-303. In: C.O. Oliver, D.P. Hanley, and J.A. Johnson, eds. Douglas-fir: Stand Management for the Future. College of Forest Resources, University of Washington, Seattle, WA.

Mitchell, J.F.B., and D.A. Warrilow. 1987. Summer dryness in northern mid-latitude due to increased CO_2. Nature 330:238-240.

Mitchell, J.F.B., C.A. Senior and W.J. Ingram. 1989. CO_2 and climate: A missing feedback? Nature 341:132-134.

Mooney, H.A., P.M. Vitousek, and P.A. Matson. 1987. Exchange of materials between terrestrial ecosystems and the atmosphere. Science 238:926-932.

Mooney, H.A., B.G. Drake, R.J. Luxmoore, W.C. Oechel and L. Pitelka. In press. How will terrestrial ecosystems interact with the changing CO_2 concentration of the atmosphere and anticipated climate change? BioScience.

Morison, J.I.L. 1987. Intercellular CO_2 concentration and stomatal responses to CO_2, pp. 229-251. In: E. Zeiger, G.D. Farquhar, and I.R. Cowan, eds. Stomatal Function. Stanford University Press, Stanford, CA.

Munslow, B., Y. Katerere, A. Ferf, and P. O'Keefe . 1988. The Fuelwood Trap: A Study of the SADCC Region. Earthscan Publ. Ltd., London. 181 pp.

Myers, N. 1988. Tropical forests and their species: Going, going ....? In: E.O. Wilson, ed. Biodiversity, National Academy Press, Washington, DC.

National Academy of Sciences. 1980. Firewood Crops. National Academy Press, Washington, DC. 236 pp.

Neilson, R.P., G.A. King, R.L. DeVelice, J. Lenihan, D. Marks, J. Dolph, B. Campbell, and G. Glick. 1989. Sensitivity of ecological landscapes and regions to global climate change. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Neilson, R.P., G.A. King, J. Lenihan, and R.L. DeVelice. 1990. The annual course of precipitation over much of the United States: Observed versus GCM simulation, pp. 19-26. In: J.L. Betancourt and A.M. MacKay, eds. Proceedings of the Sixth Annual Pacific Climate (PACLIM) Workshop, CL/PACLIM-6ATR/90-23, California Department of Water Resources, Sacramento, CA.

Newbould, P.S. 1967. Methods for estimating the primary production of forests. International Biological Program Handbook No. 2. Blackwell Scientific, Oxford.

Nohrstedt, H.-ö ., K. Arnebrant, E. Bää th, and B. Sö derströ m. 1989. Changes in carbon content, respiration rate, ATP content, and microbial biomass in nitrogen-fertilized pine forest soils in Sweden. Can. J. For. Res. 19:323-328.

Norby, R.J. Personal communication. Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, TN.

Norby, R.J. 1987. Nodulation and nitrogenase activity in nitrogen-fixing woody plants stimulated by CO_2 enrichment of the atmosphere. Physiol. Plant 71:77-82.

Norby, R.J., and E.G. O'Neill. 1989. Growth dynamics and water use of seedlings of Quercus alba L. in CO_2-enriched atmospheres. New Phytol. 111:491-500.

Norby, R.J., and E.G. O'Neill. Submitted. Leaf area compensation and nutrient interactions in CO_2-enriched yellow-poplar (Liriodendron tulipifera L.) seedlings.

Norby, R.J., E.G. O'Neill, and R.J. Luxmoore. 1986a. Effects of atmospheric CO_2 enrichment on the growth and mineral nutrition of Quercus alba seedlings in nutrient-poor soil. Plant Physiol. 82:83-89.

Norby, R.J., J. Pastor, and J.M. Melillo. 1986b. Carbon-nitrogen interactions in CO₂-enriched white oak: Physiological and long-term perspectives. Tree Physiol. 2:233-241.

Norby, R.J., E.G. O'Neill, W.G. Hood, and R.J. Luxmoore. 1987. Carbon allocation, root exudation and mycorrhizal colonization of Pinus echinata seedlings grown under CO₂ enrichment. Tree Physiol. 3:203-210.

Oades, J.M. 1988. The retention of organic matter in soils. Biogeochemistry 5:35-70.

Oberbauer, S.F., B.R. Strain, and N. Fetcher. 1985. Effect of CO₂-enrichment on seedling physiology and growth of two tropical tree species. Physiol. Plant. 65:352-356.

Odasz, A.M. 1983. Vegetational patterns at the tree limit ecotone in the upper Alatna River Drainage of the Central Brooks Range, Alaska. Ph.D. Thesis, University of Colorado, Boulder. 224 pp.

Odum, P. 1983. Basic Ecology. Saunders College Publishing, Philadelphia, PA. 613 pp.

Oechel, W., and B.R. Strain. 1985. Native species responses to increased carbon dioxide concentration. In: B.R. Strain and J.D. Cure, eds. Direct Effects of Increasing Carbon Dioxide on Vegetation. U.S. Department of Energy, Washington, DC.

Oechel, W.C., S. Hastings, D. Hilbert, W. Lawrence, T. Prudhomme, G. Riechers, and D. Tissue. 1984. The response of arctic ecosystems to elevated CO₂ regimes. U.S. Department of Energy, Carbon Dioxide Research Division Report 019, Office of Energy Research, Washington, DC.

Office of Technology Assessment. 1984. Technologies to Sustain Tropical Forest Resources. U.S. Congress, Washington, DC, 344 pp.

Office of Technology Assessment. 1987. Technologies to Maintain Biological Diversity. U.S. Congress, Washington, DC. 344 pp.

Olson, J.S., J.A. Watts, and L.J. Allison. 1983. Carbon in live vegetation of major world ecosystems. ORNL-5862, Oak Ridge National Laboratory, Oak Ridge, TN. 180 pp.

O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A Hierarchical Concept of Ecosystems. Monographs in Population Biology #23. Princeton University Press, Princeton, NJ. 253 pp.

O'Neill, E.G., R.J. Luxmoore and R.J. Norby. 1987a. Elevated atmospheric CO₂ effects on seedling growth, nutrient uptake, and rhizosphere bacterial populations of Liriodendron tulipifera L. Plant and Soil 104:3-11.

O'Neill, E.G., R.J. Luxmoore, and R.J. Norby. 1987b. Increases in mycorrhizal colonization and seedling growth in Pinus echinata and Quercus alba in an enriched CO₂ atmosphere. Can. J. For. Res. 17:878-883.

Overpeck, J.T., D. Rind, and R. Goldberg. 1990. Climate-induced changes in forest disturbance and vegetation. Nature 343:51-51.

Palm, C.A., R.A. Houghton, J.M. Melillo, and D.L. Skole. 1986. Atmospheric carbon dioxide from deforestation in southeast Asia. Biotropica 18:177-188.

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Parry, M., T. Carter, N. Konijin, and J. Lockwood. 1987. The impact of climatic variations on agriculture: Introduction to the IIASA/UNEP Case Studies in Semi-Arid Regions. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Parton, W.J., J.W.B. Stewart, and C.V. Cole. 1988. Dynamics of C, N, P and S in grassland soils: A model. Biogeochemistry 5:109-131.

Pastor, J., and W.M. Post. 1988. Response of northern forests to CO_2-induced climate change. Nature 334:55-58.

Paul, E.A. 1976. Nitrogen cycling in terrestrial ecosystems, pp. 225-243. In: O. Nriager, ed. Environmental Biogeochemistry, Vol. 1. Ann Arbor Science Publishers, Ann Arbor, MI.

Pearson, G.A. 1931. Forest types of the southwest as determined by climate and soil. Technical Bulletin 247, U.S. Department of Agriculture, Washington, DC.

Peet, R.K. 1981. Changes in biomass and production during secondary forest succession, pp. 324-338. In: D.C. West, H.H. Shugart, and D.B. Botkin, eds. Forest Succession: Concepts and Application. Springer-Verlag, New York.

Perlin, J. 1989. A Forest Journey, the Role of Wood in the Development of Civilization. Norton, New York. 445 pp.

Perry, D.A., M.P. Amaranthus, J.G. Borchers, S.L. Borchers, and R.E. Brainerd. 1989. Bootstrapping in ecosystems. Bioscience 39:230-237.

Peters, R.L., and J.D.S. Darling. 1985. The greenhouse effect and nature reserves. BioScience 35:707-717.

Peterson, C.E. Personal communication. NSI Technology Services, Corp., U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Peterson, C.E., and S.P. Gessel. 1982. Forest fertilization in the Pacific Northwest: Results of the Regional Forest Nutrition Research Project, pp. 365-369. In: R. Ballard and S.P. Gessel, eds. IUFRO Symposium on Forest Site and Continuous Productivity. General Technical Report PNW-163, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Post, W.M., W.R. Emanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature 298:156-159.

Post, W.M., J. Pastor, P.J. Zinke, and A.G. Stangenberger. 1985. Global patterns of soil nitrogen storage. Nature 317:613-616.

Postel, S., and L. Heise. 1988. Reforesting the earth. Worldwatch Paper 83, Worldwatch Institute, Washington, DC. 66 pp.

Prentice, K.C. 1990. Bioclimatic distribution of vegetation for General Circulation Model studies. J. Geophys. Res. 95:11811-11830.

Prentice, K.C., and I.Y. Fung. In press. Bioclimatic simulations test the sensitivity of terrestrial carbon storage to perturbed climates. Nature.

Prentice, I.C., R.S. Webb, M.T. Ter-Mikhaelian, A.M. Solomon, T.M. Smith, S.E. Pitovranov, N.T. Nikolov, A.A. Minin, R. Leemans, S. Lavorel, M.D. Korzukhin, J.P. Hrabovszky, H.O. Helmisaari, S.P. Harrison, W.R. Emanuel, and G.B. Bonan. 1989. Developing a global vegetation dynamics model: Results of an IIASA summer workshop. Publication RR-89-7, International Institute for Applied Systems Analysis, A-2361, Laxenburg, Austria.

Pritchett, W.L., and R.F. Fisher. 1987. Properties and Management of Forest Soils. John Wiley, New York. 494 pp.

Reid, W.V., and K.R. Miller. 1989. Keeping options alive: The scientific basis for conserving biodiversity. World Resource Institute, Washington, DC. 128 pp.

Ricklefs, R.E. 1973. Ecology. Chiron Press Inc., Newton, MA. 861 pp.

Rogers, H.H., G.E. Bingham, J.D. Cure, J.M. Smith, and K.A. Surano. 1983a. Responses of selected plant species to elevated carbon dioxide in the field. J. Environ. Qual. 12(4):569-574.

Rogers, H.H., J.F. Thomas, and G.E. Bingham. 1983b. Response of agronomic and forest species to elevated atmospheric carbon dioxide. Science 220:428-429.

Ruess, J.O., and D.W. Johnson. 1986. Acid Deposition and the Acidification of Soils and Waters. Springer-Verlag, New York. 119 pp.

Ruess, R.W., S.J. McNaughton, and M.B. Coughenour. 1983. The effects of clipping, nitrogen source and nitrogen concentration on growth responses and nitrogen uptake of an East African sedge. Oecologia (Berlin) 59:253-261.

Running, S.W., and J.C. Coughlan. 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecol. Model. 42:125-154.

Scarratt, J.B., C. Glerum, and C.A. Plexman, eds. 1982. Proceedings of the Canadian Containerized Tree Seedling Symposium, September 1981, Toronto, Canada. COJFRC Symposium Proceedings O-P-10. 460 pp.

Schlesinger, M.E., ed. 1988. Physically-Based Modelling and Simulation of Climate and Climatic Change (Part 1). Proceedings of the NATO Advanced Study Institute, Erice, Italy, May 11-23, 1986.

Schlesinger, M.E., and J.F.B. Mitchell. 1985. Model projections of the equilibrium climatic response to increased carbon dioxide. In: M.D. MacCracken and F.M. Luther, eds. Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE/ER-0237, US Department of Energy, Washington, DC.

Schlesinger, M.E., and Z.C. Zhao. 1989. Seasonal climatic change introduced by doubled CO_2 as simulated by the OSU atmospheric GCM/mixed-layer ocean model. J. Climate 2:429-495.

Schlesinger, W.H. 1977. Carbon balance in terrestrial detritus. Ann. Rev. Ecol. Syst. 8:51-81.

Schlesinger, W.H. 1984. Soil organic matter: A source of atmospheric CO_2 In: G.M. Woodwell, ed. The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing. John Wiley & Sons, New York, NY.

Schlesinger, W.H., J.F. Reynolds, G.L. Cunningham, L.F. Keunneke, W.M. Jarrell, R.A. Virginia, and W.G. Whitford. 1990. Biological feedbacks in global desertification. Science 247:1043-1047.

Schneider, S.H. 1989a. Global Warming: Are We Entering the Greenhouse Century? Sierra Club, San Francisco. 317 pp.

Schneider, S.H. 1989b. The changing climate. Sci. Amer. 261(3):70-79.

Schroeder, P.E., and L. Ladd. In press. Slowing the increase of atmospheric carbon dioxide: A biological approach. Climate Change.

Schulze, E.-D. 1989. Air pollution and forest decline in a spruce (Picea abies) forest. Science 244:776-783.

Sedjo, R. 1989. Forests to offset the greenhouse effect. J. For. 87(7):12-15.

Sedjo, R.A., and K.S. Lyon. 1990. The Long-Term Adequacy of World Timber Supply. Resources for the Future, Washington, DC. 230 pp.

Sedjo, R.A., and A.M. Solomon. 1989. Climate and forests, pp. 105-120. In: N. Rosenburg, W.E. Easterling III, P.R. Crosson, and J. Darmstadter, eds. Greenhouse Warming: Abatement and Adaptation. Resources for the Future, Washington, DC.

Shands, W.E., and J.S. Hoffman. 1987. The Greenhouse Effect, Climate Change, and U.S. Forests. The Conservation Foundation, Washington, DC.

Sharma, R.N., O.P. Vimal, H.L. Sharma, and K.S. Rao, eds. 1989. Proceedings of Bio-Energy Society Fifth Convention & Symposium '88. Bio-Energy Society of India. New Delhi, India. 486 pp.

Sharpe, J.H., R.D. Spence, and E.J. Rykiel, Jr. 1989. Diagnosis of sequential ozone effects on carbon assimilation, translocation, and allocation in cottonwood and loblolly pine. Technical Bulletin No. 565, National Council of the Paper Industry for Air and Stream Improvement, Inc., New York, NY. 76 pp.

Shugart, H.H. 1984. A Theory of Forest Dynamics. Springer-Verlag, New York, NY. 278pp.

Shugart, H.H., M.Y. Antonovsky, P.G. Jarvis, and A.P. Sandford. 1986. CO_2, climatic change and forest ecosystems - Assessing the response of global forest to the direct effects of increasing CO_2 and climatic change, pp 475-521. In: B. Bolin, B.R. Döö s, J. Jäger, and R.A. Warrick, eds. The Greenhouse Effect, Climatic Change, and Ecosystems. SCOPE 29. John Wiley & Sons, Chichester.

Simpson, G.G. 1964. Species density of North American recent mammals. Syst. Zool. 13:57-73.

Sionit, N., B.R. Strain, H. Hellmers, G.H. Riechers, and C.H. Jaeger. 1985. Long-term atmospheric CO_2 enrichment affects the growth and development of *Liquidamber styraciflua* and *Pinus taeda* seedlings. Can. J. For. Res. 15:468-471.

Sittig, M. 1979. Fertilizer Industry Processes, Pollution Control, and Energy Conservation. Noyes Data Corp., Park Ridge, NJ.

Smit, B., L. Ludlow, and M. Brklacich. 1988. Implications of a global climatic warming for agriculture: A review and appraisal. J. Environ. Qual. 17:519-527.

Smith, D.M. 1986. The Practice of Silviculture. John Wiley & Sons, New York, NY. 527 pp.

Smith, J.B., and D. Tirpak, eds. 1989. The Potential Effects of Global Climate Change on the United States. Report to Congress. EPA-230-05-89-050, U.S. Environmental Protection Agency, Washington, DC. 413 pp.

Smith, T. Personal communication. Department of Environmental Sciences, University of Virginia, Charlottesville, VA.

Smith, T.M., R. Leemans, W. Cramer, I.C. Prentice, A.M. Solomon, and H.H. Shugart. Submitted. Simulating changes in the distribution of global terrestrial vegetation under CO_2-induced climate change: Comparison among scenarios based on general circulation models. Climate Change.

Solomon, A.M. 1986. Transient response of forests to CO_2-induced climate change: Simulation modeling experiments in eastern North America. Oecologia 68:567-579.

Solomon, A.M. In press. The taiga-tundra border in first detection of biospheric response to global environmental change. In: A. Shivendko, ed. Proceedings of Boreal Forest Symposium, Arkhanglesk, USSR.

Sprugel, D.G. 1985. Natural Disturbance and Ecosystem Energetics. In: S.T.A. Pickett and P.S. White, eds. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Inc., London. 472 pp.

Stephenson, N.L. 1990. Climatic control of vegetation distribution: The role of the water balance. Amer. Naturalist. 135(5):649-670.

Stith, J.L., L.F. Radke, and P.V. Hobbs. 1981. Particle emissions and the production of ozone and nitrogen oxides from burning of forest slash. Atmos. Environ. 15:73-82.

Strain, B.R. 1987. Direct effects of increasing atmospheric CO_2 on plants and ecosystems. Tree 2:18-21

Strain, B.R., and J.D. Cure. 1985. Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238, U.S. Department of Energy, Carbon Dioxide Research Division, Washington, DC.

Surano, K.A., P.F. Daley, J.L.J. Houpis, J.H. Shinn, J.A. Helms, R.J. Palassou, and M.P. Costella. 1986. Growth and physiological responses of *Pinus ponderosa* Dougl. ex P. Laws. to long-term elevated CO_2 concentrations. Tree Physiol. 2:243-259.

Swift, M.S. 1977. The ecology of wood decomposition. Sci. Prog., Oxford 64:179-203.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. Science 247:1431-1438.

Theng, B.K.G., K.R. Tate, P. Sollins, N. Moris, N. Nadkarni, and R.L. Tate, III 1989. Constituents of organic matter in temperate and tropical soils. In: D.C. Coleman, J.M. Oades and G. Uehara, eds. Dynamics of Soil Organic Matter in Tropical Ecosystems. Niftal Project, University of Hawaii Press, Honolulu, HI.

Tinus, R.W. 1972. CO_2 enriched atmosphere speeds growth of ponderosa pine and blue spruce seedlings. Tree Planters' Notes 23:12-18.

Tinus, R.W., and S.E. McDonald. 1979. How to grow tree seedlings in containers in greenhouses, pp. 128-129. General Technical Report RM-60, USDA Forest Service, Rocky Mountain Forest & Range Experiment Station, Ft. Collins, CO.

Tissue, D.T., and W.C. Oechel. 1987. Response of Eriophorum vaginatum to elevated CO_2 and temperature in the Alaskan tussock tundra. Ecology 68(2):401-410.

Tolley, L.C., and B.R. Strain. 1984a. Effects of CO_2 enrichment and water stress on growth of Liquidamber styraciflua and Pinus taeda seedlings. Can. J. Bot. 62:2135-2139.

Tolley, L.C., and B.R. Strain. 1984b. Effects of CO_2 enrichment on growth of Liquidamber styraciflua and Pin. ·eda seedlings under different irradiance levels. Can. J. For. Res. 14:343-350.

Tolley, L.C., and . 1985. Effects of CO_2 enrichment and water stress on gas exchange of Liquidamber ɔ.. . ɛ and Pinus taeda seedlings grown under different irradiance levels. Oecologia 65:166-172.

Tranquillini, U. 1979. Physiological Ecology of the Alpine Timberline. Springer-Verlag, Berlin. 137 pp.

Trexler, M.C. In press. Reforesting the United States to Combat Global Warming. World Resources Institute, Washington, DC.

Tuhkanen, S. 1980. Climatic parameters and indices in plant geography. Acta Phytogogr. Suec. 67:1-110.

Tucker, C.J., I.Y. Fung, C.D. Keeling, and R.H. Gammon. 1986. Relationship between atmospheric CO_2 variations and a satellite-derived vegetation index. Nature 319:195-199.

Uhl, C., and C.F. Jordan. 1984. Succession and nutrient dynamics following forest cutting and burning in Amazonia. Ecology 65(5):1476-1490.

United States Department of Agriculture (USDA). 1988. The South's Fourth Forest: Alternatives for the Future. USDA Forest Resource Report #24, USDA, Washington, DC. 512 pp.

United States Department of Agriculture (USDA). 1990. Global Change Research Program Plan. USDA Forest Service, Science and Policy Associates, Washington, DC. 75 pp.

Urban, D.L., and H.H. Shugart. 1989. Forest response to climatic change: a simulation study for southeastern forests. In: J.B. Smith and D. Tirpak, eds. The Potential Effects of Global Climate Change on the United States. EPA-230-05-89-050, U.S. Environmental Protection Agency, Washington, DC.

Van Cleve, K. Personal communication. Forest Soils Laboratory, University of Alaska, Fairbanks, AK.

Vitousek, P.M., P.R. Ehrlich, A.H. Ehrlich, and P.A. Matson. 1986. Human appropriation of the products of photosynthesis. BioScience 36:368.

Waring, R.H., and W.H. Schlesinger. 1985. Forest Ecosystems: Concepts and Management. Academic Press, Inc., New York, NY. 340 pp.

Washington, W.M., and G.A. Meehl. 1989. Climate sensitivity due to increased CO_2: Experiments with a coupled atmosphere and ocean general circulation model. Climate Dynamics. 4:1-38

Webb, T. 1986. Is vegetation in equilibrium with climate? How to interpret late-quaternary pollen data. Vegetatio 67:75-91.

Webb, T. 1987. The appearance and disappearance of major vegetational assemblages: Long-term vegetational dynamics in eastern North America. Vegetation 69:177-187.

Westberg, H., K. Sexton, and D. Flyckt. 1981. Hydrocarbon production and photochemical ozone formation in forest burn plumes. J. Air Pollut. Control Assoc. 3:661-664.

Westoby, J. 1989. Introduction to World Forestry. Blackwell, New York, NY. 228 pp.

Wetherald, R.T., and S. Manabe. 1988. Cloud feedback processes in a general circulation model. J. Atmos. Sci. 45:1397-1415.

Whittaker, R.H. 1975. Communities and Ecosystems, 2nd Edition. MacMillan Publishing Co., Inc., New York, NY. 385 pp.

Whittaker, R.H., and G.E. Likens. 1975. The biosphere and man, pp. 305-328. In: Primary Productivity of the Biosphere. Ecol. Study No. 14, Springer-Verlag, Berlin.

Wiersum, K.F., ed. 1984. Strategies and Designs for Afforestation, Reforestation and Tree Planting. Centre for Agricultural Publishing and Documentation (Pudoc), Wageningen, The Netherlands. 432 pp.

Williams, W.E., K. Garbutt, F.A. Bazzaz, and P.M. Vitousek. 1986. The response of plants to elevated CO_2: IV. Two deciduous-forest tree communities. Oecologia 69:454-459.

Wilson, E.O. 1988. The current state of biological diversity, pp. 3-18. In: E.O. Wilson, ed., Biodiversity, National Academy Press, Washington, DC.

Winjum, J.K., and R.P. Neilson. 1989. Forests, pp. 71-92. In: J.B. Smith and D. Tirpak, eds. The Potential Effects of Global Climate Change on the United States. Report to Congress. EPA-230-5-89-050, U.S. Environmental Agency, Washington, DC.

Winjum, J.K., and P.E. Schroeder , eds. In preparation. Proceedings of International Workshop on Large-Scale Reforestation, May 9-10, 1990, U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Wood, P.J., J. Burley, and A. Grainger. 1984. Technologies and Technology for Reforestation of Degraded Tropical Lands. Office of Technology Assessment, U.S. Congress, Washington, DC. 114 pp.

Woodward, F.I. 1987. Climate and Plant Distribution. Cambridge University Press, London. 174 pp.

Woodwell, G.M. 1987. The warming of the industrialized middle latitudes. Unpublished manuscript, Workshop on Developing Policies for Responding to Future Climate Change, Villach, Austria. 15 pp.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, and D.T. Botkin. 1978. The biota and the world carbon budget. Science 199:141-146.

Woodwell, G.M., J.E. Hobbie, R.A. Houghton, J.M. Melillo, B. Moore, B.J. Peterson, and G.R. Shaver. 1983. Global deforestation: contribution to atmospheric carbon dioxide. Science 222:1081-1086.

World Resources Institute. 1988. World Resources 1988-89. Basic Books, Inc., New York, NY. 372 pp.

World Resources Institute. 1990. World Resources 1990-91. Oxford University Press, New York, NY. 383 pp.

Wright, L.L. In press. Short rotation woody crop opportunities to mitigate carbon dioxide buildup. In: Proceedings, North American Conference on Forestry Responses to Climate Change, May 15-17, 1990. Climate Institute. Washington, DC.

Yonker, C.M., Schimel, D.S. Paroussis, E. and R.D. Heil. 1988. Patterns of organic carbon accumulation in a semi-arid shortgrass steppe, Colorado. Soil Sci. Soc. Amer. J. 52:478-483.

Young, R.A. 1982. Introduction to Forest Science. John Wiley & Sons, New York, NY. 554 pp.

8 APPENDICES

8.1 Appendix A: Extramural Research Projects Sponsored by ERL-C Global Change Research Program in FY 90.

PRINCIPAL INVESTIGATOR	TITLE OF PROJECT	FUNDING MECHANISMS
L. H. Allen USDA/Agricultural Research Service	Temperature and CO_2 Interactions on Rates of Development, Growth, and Yield of Rice	IAG
Julio Betancourt US Geological Survey	Assist in the Organization of the 1990 Pacific Climate (PACLIM) Workshop	IAG
William Chang University of Michigan	The Effects of Long-Term Climate Changes on Large Lake Basin Ecosystems in China	Coop
Wendall P. Cropper, Jr. University of Florida	Modelling Carbon Dynamics of Slash Pine Plantations in Response to Climate Change Scenarios	Coop
James D. Hall Oregon State University	Effect of Climate Change on Inland Fisheries	Coop
James M. Hoell, Jr. National Aeronautics and Space Administration, Langley Research Center	Emissions of CH_4 and NMHC from Canadian Wetlands and Tundra Ecosystems	IAG
John Kineman National Geophysical Data Center, World Data Center	Co-develop Data, Tools, and Methods for Characterization and Analysis of Environmental System Patterns to Support the EPA's Global Climate Research and Modeling	IAG
Brian Lamb Washington State University	Biogenic Hydrocarbon Emissions and Global Climate Change	Coop
Dennis P. Lettenmaier University of Washington	Identification of Long-Term Water Resources Effects of Global Climate Change	Coop
Robert McKelvey University of Montana	Implication of the Loss of Biological and Genetic Diversity in a Regulatory Context	Coop
Ronald P. Neilson Oregon State University	Mechanisms of Biome Response to Climate Change: North American and Global	Coop
Richard J. Norby Oak Ridge National Lab	Interactions Between Elevated CO_2 and Drought Stress In Tree Seedlings	IAG

John T. Ratti University of Idaho	Potential Impacts of Climatological Change on the Distribution of Endemic Plants and Animals	Coop
David W. Roberts Utah State University	Assessing the Effects of Climate Change on Forest Ecosystem Dynamics	Coop
Steve Running University of Montana	Coupling of Forest-BGC FORET Ecosystem Simulation Models for Projection of Forest Responses to Global Climate Change	Coop
Herman Shugart University of Virginia	Linking Physiological Process Models to Forest Gap Models	Coop
Fredrick Swanson USDA/Pacific NW Station	Technology Transfer and Cooperative Research on Western Forests	IAG
John M. Thomas Battelle/Pacific NW Lab	Technology Transfer and Cooperative Research in Support of EPA's Global Climate Change Program	IAG
Starley Thompson National Center for Atmospheric Research	Modeling the Effects of Global Climate Change on Vegetation: Non-Interactive and Interactive Responses	Coop
Ted Vinson Oregon State University	Carbon Cycling in Arctic Tundra and Boreal Forest Ecosystems: Responses and Feedbacks to Global Climate Change	Coop

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8.3 Appendix C: Invited Participants, Workshop on Ecological and Operational Considerations for Large-Scale Reforestation, Corvallis, Or. May 8-10, 1990

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8.4   Appendix D: Abbreviations

CEES	Committee on Earth and Environmental Sciences
DOE	Department of Energy
EPA	Environmental Protection Agency
ERL-C	Environmental Research Laboratory-Corvallis
FAO	Food and Agriculture Organization
FY	Fiscal year
GCM	General Circulation Model
GIS	Geographic Information System
GCRP	Global Change Research Program
GFDL	Geophysical Data Center
GISS	Goddard Institute for Space Science
IPCC	Intergovernmental Panel on Climate Change
MAI	Mean annual increment
NEP	Net ecosystem productivity
ORD	Office of Research and Development
OSU	Oregon State University
OTA	Office of Technology and Assessment
PAR	Photosynthetically active radiation
PET	Potential evapotranspiration
TSI	Timber stand improvement
UKMO	United Kingdom Meteorological Organization
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USFS	USDA Forest Service
WUE	Water-use efficiency